Evaluation of Roadway Lighting Practices

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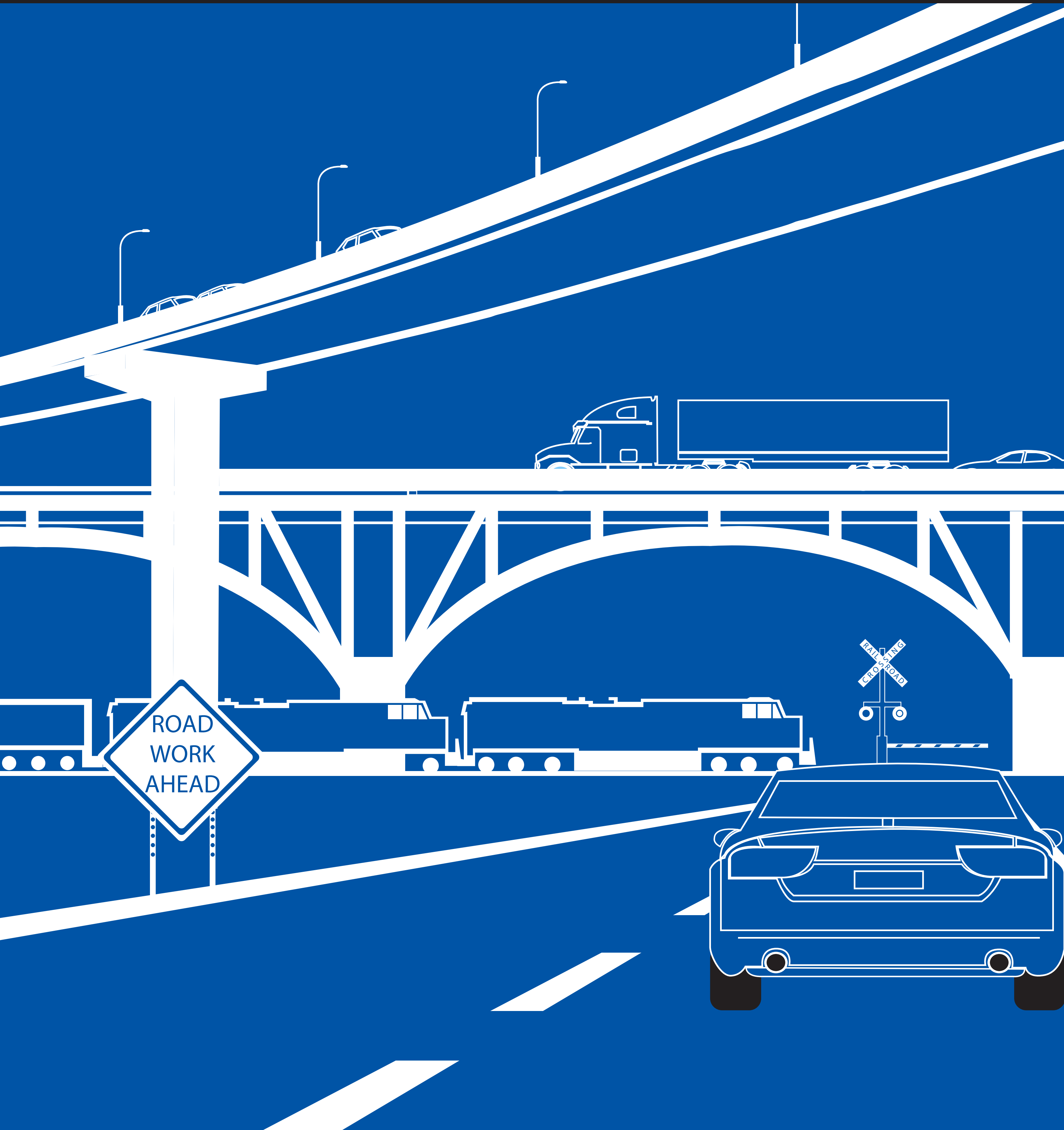

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report

KTC-17-23/RSF45-17-1F

Evaluation of Roadway Lighting Practices

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16. Abstract

Adequate roadway lighting allows better driver visibility during nighttime conditions. Research studies show that lighted roadways on average experience 28 percent fewer vehicles crashes on all roadway types. Most state DOTs have historically used High-Pressure Sodium (HPS) lights for their roadside lighting programs due to their wide availability and relatively low purchase costs. However, the short lifespan of HPS results in frequent replacement, leading to high life cycle costs. Light-Emitting Diode (LED) lights consume less energy, demonstrate improved performance, and require less overall maintenance due to their longer lifespans. Over time, this translates into maintenance cost savings for state DOTs. In recent years, several state and local governments have begun increasing their use of LED lighting. KTC reviewed other state's best practices for roadway lighting and assisted KYTC with analyzing the performance differences between HPS and LED. KTC also compiled a statewide roadside lighting inventory through coordination with each KYTC district. After developing the full inventory, the research team conducted light surveys at locations across Kentucky. The light surveys confirmed that LED lights routinely outperform HPS lights. It is recommended that Kentucky continue to transition to LED lighting, find a method for keeping the statewide lighting inventory up to date, and specify light spacing for new installations.

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EXECUTIVE SUMMARY

State Departments of Transportation (DOTs) regularly establish highway lighting programs to advance safety outcomes and reduce crashes. Adequate roadway lighting allows drivers better visibility during nighttime conditions, as illustrated by research studies that show lighted roadways on average experience 28 percent fewer vehicles crashes on all roadway types. Most state DOTs have historically used High-Pressure Sodium (HPS) lights for their roadside lighting programs due to their wide availability and relatively low purchase costs. However, the short lifespan of HPS (approximately four years) results in frequent replacement, leading to high life cycle costs. Light-Emitting Diode (LED) lights consume less energy, demonstrate improved performance and an output similar to HSP, and require less overall maintenance due to their longer lifespans (more than 10 years). Over time, this translates into maintenance cost savings for state DOTs.

In recent years, several state and local governments have begun increasing their use of LED lighting. KTC reviewed other state's best practices for roadway lighting and found several states that have gravitated towards replacing HPS lights with LED lights. California, Kansas, New York, and Indiana are four states currently undergoing roadway lighting program changes. CalTrans showed dramatic safety improvements at pilot locations using LED lighting; specifically, reduced nighttime crashes. The state decreased the amount of maintenance required on HPS lights — which had a service life of about 5 years — compared to LED lights with a service life of 14 years.

KTC researchers assisted KYTC with analyzing the performance differences between HPS and LED, and compiled a statewide roadside lighting inventory through coordination with all twelve KYTC districts. The research team standardized the light inventory database across multiple attributes and plotted all results into ArcGIS. Upon completion of the light inventory, the team identified and conducted light surveys at locations across Kentucky. The survey coupled HPS and LED light sources with light types, to include four measurement categories: HPS cobra, LED cobra, HPS high-mast, and LED high-mast. Measurements were taken at set intervals along roadways, as recommended in guidance from the American Association of State Highway and Transportation Officials (AASHTO) and the Illuminating Engineering Society (IES). The research team used a light illuminance meter and laser distance measuring device to record illuminance levels that were based on the following KYTC illuminance design standards:

- Average maintained illuminance on all roadway surfaces of 0.80 foot-candles
- Minimum illuminance of 0.20 foot-candles
- Uniformity ratio less than or equal to 4:1

The study showed that LED conventional lights routinely outperform HPS conventional lights. Although there is not a current spacing specification for new installments of LED lighting, LED conventional lights meet the KYTC minimum illuminance design standard at increased longitudinal light spacing of $\leq$ 178 feet, compared to HPS conventional lights spaced at $\leq$ 120 feet.

It is recommended that KYTC specify the longitudinal light spacing of new installations of conventional LED lights in order to meet KYTC minimum illuminance design standards.

Based on a small sample size, LED high-mast lights appear to outperform HPS high-mast lights. Additional research on larger samples could examine differences and confirm this finding. KTC also recommends that district offices use a standard format when updating their roadside lighting inventory and share all updates with the Division of Traffic Operations in a timely manner. These findings on performance and lighting inventory should better inform KYTC decision makers on future budget and policy decisions related to the roadway lighting program.

1. BACKGROUND

1.1 Introduction

Roadway lighting illuminates nighttime driving conditions to allow increased driver visibility and promote a safer driving environment. Transportation research studies have shown that roadway lighting helps decrease vehicle crashes across all roadway types. For example, the Highway Safety Manual (HSM) estimates a crash modification factor of 0.72 for lighted roadways in preventing nighttime injury crashes, compared to roadways without lighting.[1] This means that on average, lighted roadways experience 28 percent fewer injury crashes compared to non-lighted roads. Consequently, state DOTs regularly employ highway lighting to advance safety outcomes and reduce crashes. State DOTs rely upon lighting guidelines issued by the American Association of State Highway and Transportation Officials (AASHTO) and Illuminating Engineering Society (IES) to shape their lighting programs. These guidelines provide recommendations on minimum lighting levels required for sufficient visual acuity and safe navigation conditions.

Historically, state DOTs employed the use of High-Pressure Sodium (HPS) lights for their roadside luminaires due to their wide availability and relatively low purchase costs. However, their limited lifespan (approximately four years) led to frequent replacements, resulting in higher life-cycle costs. State DOT officials saved money during initial installations but found lighting programs were less cost effective than initially perceived due to frequent HPS light replacements. In recent years, several state and local governments have begun increasing their use of Light-Emitting Diode (LED) lights due to cost and performance improvements.

LED lights have traditionally been cost prohibitive and greatly exceeded the initial purchase costs associated with HPS lights. However, prices of LED lights have rapidly decreased in recent years, bringing their price in closer parity with HPS lights. Further, LED lights consume less energy and require less overall maintenance due to their longer lifespans, which typically exceed 10 years. Over time, this translates into maintenance cost savings for state DOTs. LED lights have demonstrated improved performance over the last two years by select manufacturers who have produced LED lights with comparable light output to traditional HSP lights. Prior to this time, there were concerns with whether LED lights could meet minimum light threshold requirements. LED lights employ a concept called adaptive lighting, which allows them to be dimmed or brightened at different times during the night. Several state DOTs have experimented with dimming LED lights during nighttime, low-traffic volume conditions, yet the lights still adhere to minimum lighting standards. The reduced power demands in this practice can yield significant cost savings. Overall, LED lights may be appropriate and advantageous to state DOTs within certain roadway constraints, but research into this emerging field continues to develop.

1.2 Problem Statement

Roadway lighting represents a safety improvement to nighttime driving conditions and promotes increased visibility for driver navigation. Transportation decision makers recognize the safety benefits of roadway lighting and subsequently devote significant funding to the installation, operation, and maintenance of roadway lighting. Recent advances in LED lighting technology have prompted many state and local governments to transition from traditional HPS lights to LED lights. The Kentucky Transportation Cabinet (KYTC) has also begun installing LED lights at a limited number of locations throughout the state. Going forward, KYTC seeks to assess the performance differences between HPS and LED lights on state-maintained roadways, and will compare findings to practices currently documented in KYTC's policies and design standards. The results from this analysis should better inform KYTC decision makers on performance and budgetary actions in the future. Finally, KYTC needs an updated and comprehensive compilation of the entire statewide roadside lighting inventory, which is currently fragmented across the individual districts.

1.3 Objective

The Kentucky Transportation Center (KTC) investigated existing KYTC roadway lighting infrastructure, practices, and policies. The following tasks were completed to support this objective:

- Conduct literature review for roadway lighting best practices
- Develop a KYTC roadside lighting inventory
- Evaluate existing KYTC roadside lighting through light surveys
- Document study results

2. LITERATURE REVIEW

2.1 AASHTO

The American Association of State and Highway Transportation Officials (AASHTO) publishes the Roadway Lighting Design Guide as an authoritative manual on roadside lighting programs and practices.[2] This manual provides the foundation for many transportation authority lighting programs, including lighting design. Roadside lights, or luminaires, should be designed to maximize visibility to the driving public. Light levels for human visual acuity are typically measured in one of two forms: illuminance and luminance. Illuminance measures light on a roadway surface in terms of foot-candles (or Lux). Luminance accounts for light levels reflected from the roadway and visible to the human eye. Both measures may be recorded along a roadway at set intervals. AASHTO recommends obtaining light readings between two light sources, or one luminaire cycle (shown in Figure A below).

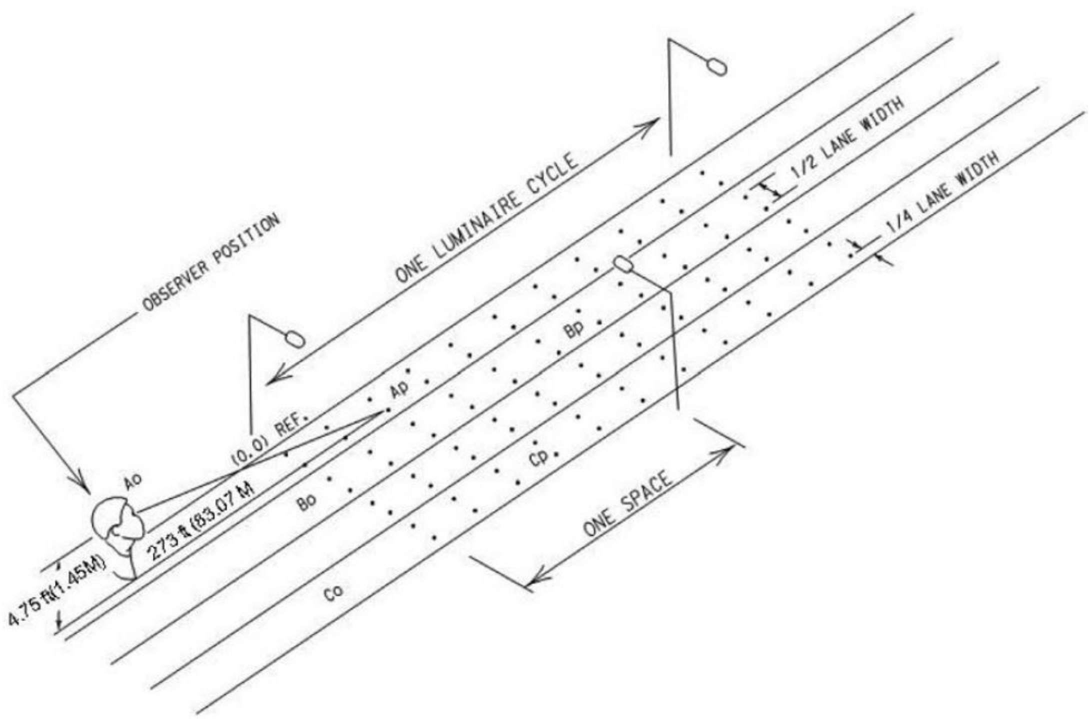


Figure A: Calculation Points for Luminance and Illuminance Design Methods, AASHTO Roadway Lighting Design Guide

The number of measured recordings should be approximately the length of the luminaire cycle divided by ten. In equation form, this is:

Number of Points = Luminaire Cycle Distance / 10

Additional recordings may be necessary if intervals exceed 15 feet. Illuminance measurements should take place near the pavement surface, while luminance measurements would take place at 4.8 feet above the surface, or the typical motorist eye height.

AASHTO provides state transportation authorities with recommendations on continuous roadside lighting requirements. AASHTO tables categorize lighting thresholds by illuminance and luminance values for various roadway classifications (principal arterials), including two critical values: the minimum illuminance level and the uniformity ratio. The former describes a minimum level of perception for drivers so they can observe roadside hazards while the latter describes consistency between the bright and dim spots within a luminaire cycle. Higher critical light values may be needed for locations with higher traffic volumes or hazards, including interchanges and intersections.

2.2 Illuminating Engineering Society (IES)

The Illuminating Engineering Society (IES) provides the second authoritative manual on roadside lighting programs and standards. IES publishes a Roadway Lighting manual (2014) that provides design guidelines for roadways, streets, and other transportation pathways with lighting needs.[3] Similar to AASHTO, this manual identifies potential hazards associated with nighttime driving conditions and develops lighting countermeasures to mitigate those safety issues.

The IES Roadway Lighting manual utilizes similar lighting measurement concepts as the AASHTO manual, including the use of illuminance and luminance. In fact, the manual recommends collecting lighting measurements along roadway pathways between adjacent light sources, better known as a luminaire cycle, matching the AASHTO methodology for recording light output on lighted roadways. The IES manual also provides additional guidelines not found in the AASHTO guidance. For instance, the required luminance values by street classification are further subdivided by the pedestrian traffic within an area. In another example, illuminance thresholds are provided for both intersections and interchanges by functional classification. This additional precision better informs transportation professionals when they make decisions about lighting requirements along their transportation network.

2.3 Federal Highway Administration (FHWA)

Federal highway funding may be used for roadside lighting projects by state DOTs, once documentation requirements are met. In these cases, FHWA recommends that transportation authorities provide either a lighting warrant analysis or a document indicating conformance with AASHTO or IES lighting guidelines.[4] Warrants pertaining to roadside lighting are available for highways, freeways, interchanges, and bridges through the AASHTO Roadway Lighting Design Guide.[2] The warranting selection process considers traffic volumes, interchange spacing, ambient lighting, and night-to-day crash ratios. Lower functional level roadways such as collectors and local streets rely on guidance from the Transportation Association of Canada (TAC) Guide for the Design of Roadway Lighting.[5] This manual focuses primarily on geometric (e.g., grade, number of lanes, etc.) and operational (e.g., signals, speed, etc.) factors for roadside lighting warrants.

Transportation authorities must also take into account lighting level when determining the need and amount of light required on a roadway. For instance, while minimum lighting helps increase visibility for nighttime drivers, too much lighting may negatively impact local conditions through sky glow. Excessive light reflected from a given light source illuminates the atmosphere and may interfere with the natural habitat, sleeping patterns, or natural conditions of humans, animals, or plants in the area. For these reasons, prevailing lighting guidance provides recommended minimum and maximum lighting levels based on need and conditions.

2.4 Roadside Lighting Studies

Several state departments of transportation have evaluated transitioning their roadside lighting from traditional HPS to LED lights. Performance improvements, reduced maintenance costs, and increased flexibility have all been cited as reasons for these moves. In these efforts, different states are at different implementation phases for their roadside lighting transitions. Several states have aggressively moved forward with replacing HPS lights with LED lights, while others are further evaluating the true costs and benefits involved. California, Kansas, New York, and Indiana represent four states currently undergoing roadway lighting program changes.

The California Department of Transportation (CalTrans) conducted a freeway performance improvement initiative where investigators evaluated roadway lighting changes that took place from 2000 through 2011.[6] The purpose of this study was two-fold. First, officials assessed improvements in safety outcomes during pre- and post-lighting installation periods. Second, officials wanted to understand the differences between HPS and LED light installations in terms of performance. CalTrans assessed lighting options at several pilot locations that showed dramatic safety improvements; specifically, reduced nighttime crashes. The study demonstrated significant improvements in maintenance when lights were converted from HPS to LED. For example, CalTrans HPS lights typically had a full-service life of 20,000 hours or approximately 5 years under normal lighting conditions. LED lights, however, had an increased service life of 50,000 hours or about 14 years. This resulted in significant cost savings over the long-term, and CalTrans decided to replace HPS lights with LED lights over time.

The Kansas Department of Transportation commissioned researchers from the University of Kansas to evaluate roadway lighting and to assist in the development of a highway lighting manual. In this effort, they compared energy cost savings between the older HPS lights on their network and the new LED lights scheduled for replacement. The study found that LED lights outperformed HPS lights in maintenance costs and over a 12-year period, Kansas DOT could save approximately $47.68 per year per light.[7] These cost savings exceeded any initial differences between the slightly more expensive LED lights when compared to HPS lights.

In 2014 and 2015, the New York State Department of Transportation evaluated potential retrofit options for transitioning their existing HPS lighting to LED lighting. The Lighting Research Center (LRC) at the Rensselaer Polytechnic Institute used their lighting expertise to carry out this study.[8] LRC took field illuminance measurements at intervals along three roadway locations and analyzed lighting photometrics and energy outputs. Existing roadway HPS lights were examined in terms of average and minimum illuminance levels. The three locations had average illuminance levels of 0.55, 0.68, and 0.35 foot-candles, respectively. The three locations also demonstrated minimum illuminance levels of 0.30, 0.29, and 0.11 foot-candles, respectively. Researchers also assessed how different LED manufacturers would similarly perform at the locations. In each case, the team found at least one product that would out-perform current lighting standards of the existing HPS lighting setup. Finally, the research team conducted an economic analysis of the sampled locations by comparing energy outputs and associated potential savings. This analysis examined the full life-cycle costs for lights including initial luminaire cost, installation cost, and energy savings. A simple, one-for-one swap without any changes in lighting procedures (i.e., how and when they were used) averaged a 5.7 year payback period. The use of adaptive lighting yielded a lower payback period of approximately 5.1 years.

The Indiana Department of Transportation collaborated with Purdue University to examine several lighting technologies: HPS, LED, induction, and plasma. The researchers conducted a literature review, surveyed state and local transportation officials, and tested lighting characteristics across a range of lighting products.[9] Similar to other studies, they found that HPS lights possessed several advantages including low initials costs, wide availability, and versatility for use in broad applications. On the other hand, HPS lights demonstrated limitations through inadequate color rendering, slow start-up times, and increased maintenance. LED lights often served as a counterpoint to HPS light technology through their own distinct strengths and weaknesses. LED lights have higher initial purchase costs (though costs have declined in recent years) but longer lifespans. They have many advantages: high energy conversion efficiency, strong color rendering, reduced energy consumption, expedited start-up times, and light threshold adjustment capabilities. LED lights have a few disadvantages including higher initial costs, thermal management constraints due to higher ambient temperatures causing overheating, and photobiological concerns through potential Illuminating Engineering Society of North America (IESNA) safety exceedances that may harm the human eye.

2.5 Adaptive Roadside Lighting

Adaptive lighting technology allows state DOTs to adjust lighting illumination levels based on prevailing traffic conditions. Often, newly installed LED lights illuminate at higher levels than needed for sufficient object contrast and overall driver visibility. Unlike traditional HPS lights, LED lights may be dimmed to lower illumination levels. Dimming the lights results in less energy consumption and significant cost savings to the state DOT, while still meeting necessary lighting thresholds identified by AASHTO and IES to provide safe driving conditions.

Adaptive lighting technology relies on interconnected control systems to adjust LED light levels. Each luminaire is equipped with an individual module, which connects to a home base controller. The person monitoring the control system may adjust the light output for each luminaire within the network, as needed. Other methods also exist to dim lighting levels along a roadway segment. One such method, luminaire extinguishing, consists of turning off every other light along a corridor or all lights on just one side of a roadway (when luminaires exist on both sides). Light extinguishing may reduce energy consumption to an even greater degree than adaptive roadside lighting. However, these methods are not recommended due to their greater difficulty in meeting lighting standards.[10] Several transportation authorities have started exploring the use of LED adaptive lighting to suit their needs, including the Washington State DOT, New York State DOT, and the city of Pittsburgh.

In 2013, the Washington State DOT initiated a study to examine the benefits of transitioning their HPS roadway lighting network to LED lights with a focus on adaptive lighting capabilities. Washington officials estimated that they spend nearly $5.5 million and $8 million annually on maintenance and life-cycle replacement costs, respectively. Electricity consumption equals nearly $4 million of the total costs. In a pilot study, DOT officials installed adaptive roadside lighting along a state highway corridor resulting in a 74 percent reduction in electricity consumption. Deemed a success, officials have now rolled out their study to more than a dozen other locations across the state. The results from these ongoing initiatives will better inform officials on their strategy for moving forward with LED adaptive lighting.[11]

Researchers from the Lighting Research Center at the Rensselaer Polytechnic Institute evaluated adaptive lighting strategies for the New York DOT in 2015. Their overarching goal was to determine how adaptive lighting strategies might be implemented to meet IES standards while still generating significant long-term cost savings for the DOT. In this effort, adaptive lighting could be implemented during late night hours when the classification of a roadway changed to a lower functional category. For example, significant traffic volume reductions at night might downgrade a major roadway functional category to simply a local road. In this case, the light illumination could be reduced by up to 50 percent resulting in a nearly 30 percent energy cost savings. The research team further evaluated the time it would take to realize a breakeven point or payback period from the initial LED light and adaptive controls installation costs. They assessed five lighted corridors and found relatively brief payback periods for each. This included three corridors with a payback period of 4 years and two corridors with a payback period of 5 years, respectively.[8]

The city of Pittsburgh replaced nearly 4,500 existing HPS lights with LED lights between 2012 and 2016. In this effort, they have enlisted the research and technical capabilities of Carnegie Mellon University to assist in identifying LED lighting components and coordinating its lighting program transition. Carnegie Mellon researchers conducted a detailed market study on currently available LED light system components and their capabilities, and discovered that adaptive lighting systems have advanced their capabilities significantly in recent years. Lighting controls represent the infrastructure that allows operators to sense and adjust lighting levels to the desired level. Lighting controls may include sensors, meters, audio/visual, Wi-Fi and telecommunications, and any other interface between the LED light and the operator. Modern lighting controls allow the operator to conduct remote dimming and on/off control. The dimming option features adjustment between 0 to 100 percent (within 1 percent accuracy). The operator may also set specific schedules for light dimming by days, hours, and other sensor-based events (e.g., ambient light levels). The operator accesses light readings and controls output through its central management software. The software provides historical and up-to-date data on many lighting characteristics useful to transportation officials. Several commonly recorded measures include total hours of operation, total energy consumption, dimming levels over time, and critical events, such as a light failure.[12]

3. ROADSIDE LIGHTING DATABASE

3.1 Methodology

KYTC is responsible for installing and maintaining roadway lighting along state-maintained roads. The central office delegates these responsibilities to local district offices across the state. Initially, KTC researchers coordinated with the central office's Division of Traffic Operations, which oversees the roadside lighting program. Leaders within the Division of Traffic Operations provided the research team with roadside lighting points of contact for each district. Over the following month, the research team contacted all twelve districts and requested a roadside lighting inventory. Some districts had readily accessible roadside lighting inventories on hand, while others had to develop them based on a format prescribed by KTC. Each lighting inventory included the following attributes: county, county code, route unique, beginning mile point, ending mile point, light type (conventional or high-mast), light source (HPS, LED, or other), light number, intersection or interchange, and exit number (if applicable). The tables below represent a typical cross-section of inventory attributes obtained from the different district offices.

County	County Code	Route Unique	Route Mile Point		Roadway Light	
			Begin	End	Light Type (Conventional, High Mast)	Light Source (HPS, LED, other?)
Bath	6	006-I -0064 -000	120.9	121.6	HM	HPS
Bath	6	006-I -0064 -000	122.6	123.4	Cobra	HPS
Boone	8	008-KY-0842 -000	7.55	7.6	Cobra	HPS
Boone	8	008-KY-0237 -000	11.4	11.45	Cobra	HPS
Boone	8	008-KY-1017 -000	0.2	0.8	Cobra	HPS
Boone	8	008-I -0071 -000	71.8	72.4	Cobra	HPS
Boone	8	008-I -0075 -000	172.3	173.3	Cobra	HPS
Boone	8	008-KY-0237 -000	11.8	11.9	Cobra	HPS

Table 1: KYTC Lighting Inventory, Dataset Example (First Half)

Number of Luminaires	Route	Intersection	Exit (if applicable)	District
40	I-64	I-64 @ KY 36	121	9
58	I-64	I-64 @ US 60	123	9
4	KY-0842	KY 842 Park/Ride	N/A	6
4	KY-0237	KY 237 Park/Ride	N/A	6
22	KY-1017	KY 1017 (Turfway Road) Overpass	182 (N)	6
30	I -0071	Verona	72	6
31	I -0075	I-71/75 Split	173	6
34	KY-0237	KY 237 Roundabouts	N/A	6

Table 2: KYTC Lighting Inventory, Dataset Example (Second Half)

3.2 KYTC Database

In total, the district offices provided the research team with 576 individual locations of state-maintained roadside lights. The number of lights at each location varied significantly; one location could have a single roadside light, where another location could have hundreds of lights. Eight inventoried locations had a single light, which is typically found in rural counties with low population/density counts. Seven roadside locations contained over 200 lights. The two highest light counts (284) were both located in Jefferson County at the I-65 interchange with I-265 and at the I-65 interchange with KY 841. Typical light counts are best represented through two statistical measures: average and median. The average light count across the full roadside lighting inventory is 44.9, or approximately 45 luminaires per given location. The median count represents the middle value across the full light inventory. The median roadside light count for the entire inventory is 32, meaning that exactly half of roadside light locations have more lights and half have fewer lights.

The research team plotted the final roadside light inventory to ArcGIS using the defined attributes. For comparison, the light inventory was categorized by light source and light type across six combinations. Those categories include: (1) LED high-mast / HPS cobra, (2) LED high-mast, (3) LED cobra, (4) HPS cobra / high-mast, (5) HPS high-mast, and (6) HPS cobra. The overwhelming percentage of KYTC roadside lights are found along major interstates throughout the state. This overall KYTC roadside lighting depiction is shown in Figure B. The final ArcGIS plots and accompanying data were provided to the Kentucky Transportation Cabinet as a project deliverable.

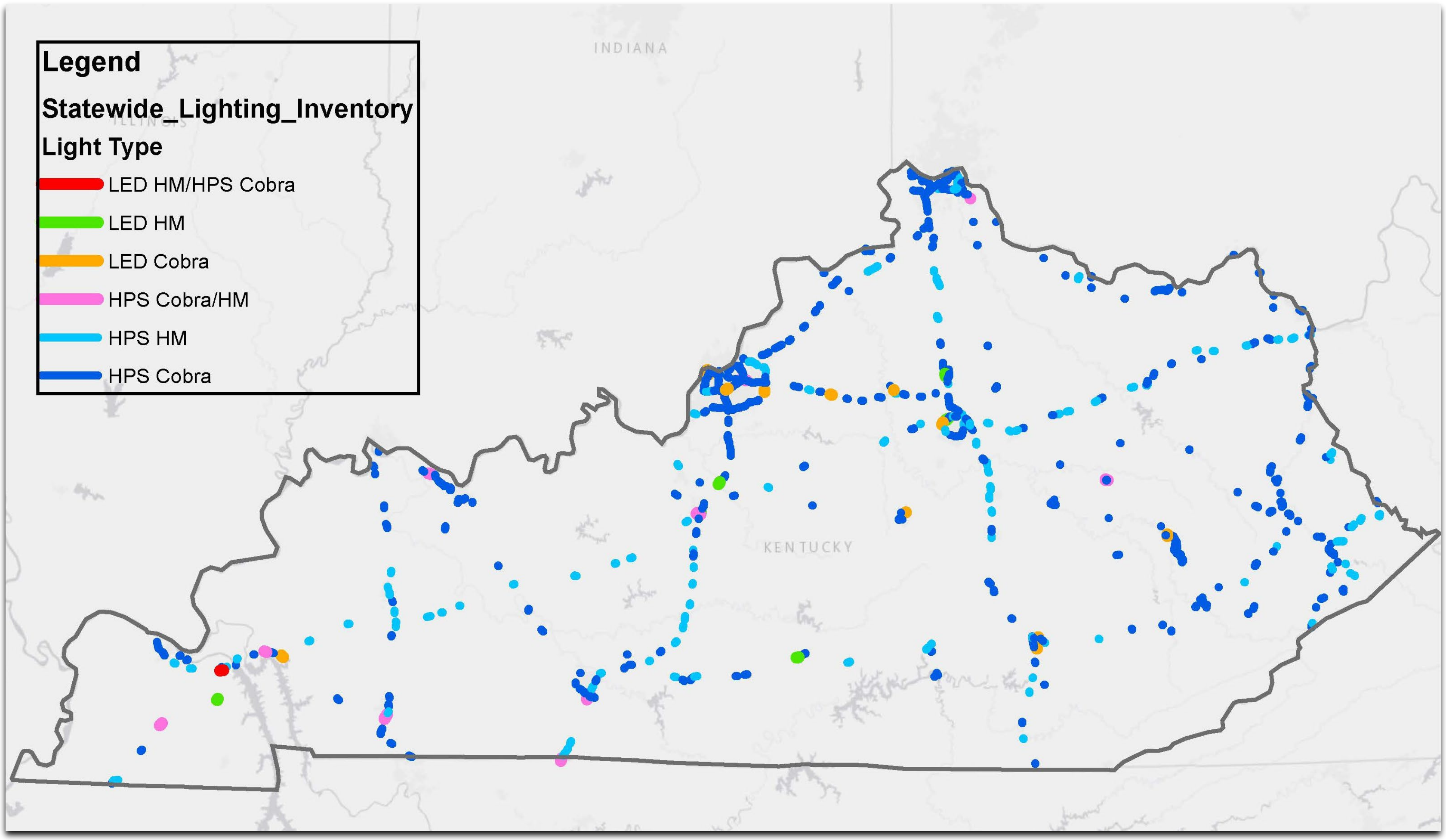


Figure B: Kentucky Transportation Cabinet Roadside Lighting Inventory, 2017

4. ROADSIDE LIGHT SURVEYS

4.1 Light Performance

Roadside lighting along Kentucky routes assists drivers with safely navigating low-visibility nighttime conditions. KYTC has adopted minimum roadside lighting design standards and policies consistent with nationally-recognized safety guidelines. Specifically, KYTC adheres to roadside lighting design standards and guidelines developed by AASHTO and IES.

Traditionally, high-pressure sodium (HPS) lights have been used across Kentucky. This adoption was consistent with nationwide best practices since HPS lights represented the best combination of performance and cost-effectiveness. In recent years, LED lighting technology has increased in popularity as its performance, or light output, has improved and the cost of LED has decreased. Several state departments of transportation and local governments have—in turn—transitioned to LED light installations within their respective jurisdictions. KYTC has started installing LED lights across select locations as it moves away from HPS. In the first phase of this project, KYTC tasked the KTC research team to assess the performance differences between HPS and LED lights at selected locations across Kentucky.

4.2 Methodology

The research team developed a light survey to assess the performance differences between HPS and LED lights for state-maintained roadways. This survey coupled light sources (HPS and LED) with light types (conventional and high-mast) to create four main categories, listed below.

1. HPS conventional
2. HPS high-mast
3. LED conventional
4. LED high-mast

The KYTC roadside lighting inventory contained hybrid combinations within these four categories: (1) LED high-mast/HPS cobra and (2) HPS high-mast/cobra. However, due to their very limited numbers, the research team did not conduct light surveys on these unique hybrid categories.

Using the original four-category list, the research team identified locations across Kentucky to assess and compare HPS and LED performance characteristics. These locations represent a geographically diverse cross-section of Kentucky's lighted roadways. The full light survey list by location is shown in Table 3 below.

ID Number	Location			Date	Type
	Roadway Site	Latitude	Longitude		
1	New Circle Rd (Outer Loop) at Harrodsburg	38.01737	-84.55192	11/15/2016	HPS Cobra
2	I-64 EB Midway Rest Stop Ramp	38.16980	-84.76909	12/1/2016	HPS Cobra
3	I-64 EB Midway Rest Stop Lot	38.16909	-84.76651	12/1/2016	HPS Cobra
4	KY 841 EB at New Cut	38.11928	-85.77595	12/8/2016	HPS Cobra
5	KY 841 EB at New Cut	38.11938	-85.77550	12/8/2016	HPS Cobra
6	KY 151 at I-64 NB/SB	38.14543	-84.98995	12/19/2016	HPS Cobra
7	KY 151 at I-64 NB/SB	38.14611	-84.99017	12/19/2016	HPS Cobra
8	I-75 at Exit 49	37.22559	-84.21242	1/18/2017	HPS Cobra
9	I-75 at Exit 49	37.22587	-84.21279	1/18/2017	HPS Cobra
10	I-71 at Exit 2	38.27348	-85.69867	1/25/2017	HPS Cobra
11	I-71 at Exit 2	38.27375	-85.69804	1/25/2017	HPS Cobra
12	New Circle Rd (Inner Loop) at Versailles	38.04385	-84.56626	11/15/2016	LED Cobra
13	I-265 EB at Taylorsville	38.18907	-85.50698	12/8/2016	LED Cobra
14	I-265 EB at Taylorsville	38.18920	-85.50649	12/8/2016	LED Cobra
15	I-64 EB Weigh Station	38.17113	-85.15553	12/19/2016	LED Cobra
16	Hal Rogers at North Laurel High School	37.14532	-84.07862	1/18/2017	LED Cobra
17	Hal Rogers at North Laurel High School	37.14529	-84.07894	1/18/2017	LED Cobra
18	US 421 at US 60	38.18865	-84.82085	1/25/2017	LED Cobra
19	US 421 at US 60	38.18868	-84.82026	1/25/2017	LED Cobra
20	Cumberland Pkwy WB at KY 127	37.05063	-85.07463	12/14/2016	HPS HM
21	I-275 at Exit 76	39.03752	-84.46989	1/19/2017	HPS HM
22	I-24 at US 62	37.00377	-88.32328	1/27/2017	HPS HM
23	Cumberland Pkwy WB at KY 61	37.07334	-85.34338	12/14/2016	LED HM

Table 3: Light Surveys

The light surveys evaluated illuminance measurements per KYTC's lighting design standards across the following metrics:

- Average maintained illuminance on all roadway surfaces of 0.80 foot-candles
- Minimum illuminance of 0.20 foot-candles
- Uniformity ratio less than or equal to 4:1[13]

The research team used a light illuminance meter and laser distance measuring device to gather data for the survey. The T-10 Minolta illuminance meter collects light through a light receptacle and displays the illumination strength on an outer display screen. It measures the illuminance levels at a given location and accounts for the light angle of impact. The device can measure both continuous and intermittent light sources. It also can switch between light measurement units (lux and foot-candles) and works across a wide range of light measurements (between 0.01 and 299,900 lux).[14] The laser distance measuring device, a Bosch GLM 80 lithium-ion laser distance measurer, allows the user to point a laser at a pole head and obtain its height. The device can report accurate distances between roadside lights (Figure C), provides measurements in feet, and is capable of measuring up to 265 feet within 1/16 inch accuracy.[15]

Figure C: KTC researcher measuring distance between light poles

Team members obtained light measurements along travel pathways using AASHTO and IES lighting measurement practices.[2,3] Each travel pathway was ¼ lane width from the edge of the travel lane. This study primarily used measurement locations along the 12-foot travel lanes found on interstates and interchanges, where each travel lane pathway was approximately 3 feet from the edge of the travel lane marking. This methodology was employed across all inventoried locations since the majority contained these travel lane widths.

Individual travel lane pathways began with the initial roadside light location and ended with the final roadside light location. This full pathway is known as one luminaire cycle, per AASHTO guidance. A planar two-lane graphical depiction for these measurement pathways is shown in Figure D below. Each measurement pathway is represented by a dashed red line, and the two measured roadside lights are represented by the two yellow cylinders. It should be noted that individual light locations contained varying lane counts from a single-lane up to four-lanes (see Appendix A for full list).

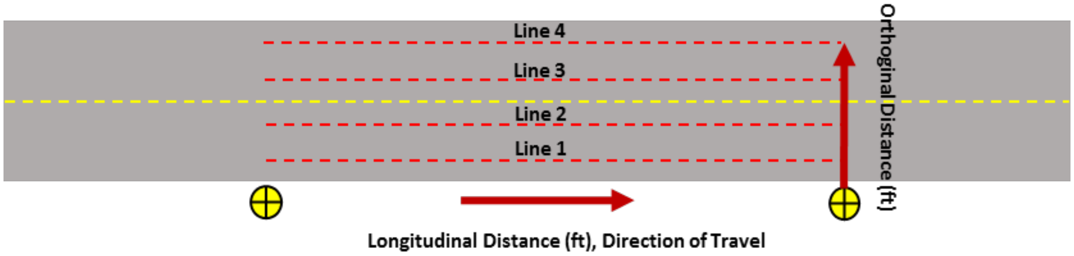


Figure D: Light Measurement Pathway

Team members collected ten measurements across each travel pathway when moving between the two light sources. The number of measurements were found by dividing the overall longitudinal distance between lights, or luminaire light cycle, by a factor of 10. For example, two roadside lights placed 200 feet apart would correspond to 20-foot spacing light measurements.

Once spacing and measurement points were known, team members employed the following steps to collect the individual measurements:

1. Turn the power on
2. Remove light cap over light receptor
3. Calibrate the meter using the zero adjustment option
4. Place light receptor at proximal, parallel location to roadway surface for light survey reading (see Figure E)
5. Press hold button for appropriate light measurement reading (run state for continuous readings and hold state for paused reading)
6. Measure light illuminance reading in foot-candles

Figure E: KTC researcher obtaining survey reading for HPS cobra light

4.3 Light Surveys

4.3.1 HPS Cobra Lights

The research team collected HPS cobra light measurements at eleven individual roadside lighting locations that were defined by a distinct ID number. These lights met, or nearly met, conventional light height requirements (30-40 feet) per KYTC policy.[13] All roadside light heights within this group ranged between 28 to 31 feet and were considered the standard conventional height for purposes of this study. Per the methodology, light measurements were collected at 10 equally (or nearly equally) spaced segments along each travel lane pathway. A single travel lane would include two pathways and each additional travel lane corresponded to two additional pathways (e.g., four pathways for two travel lanes). The complete lighting dataset for all light survey measurements can be found in Appendix A. Tables 4 and 5 summarize the recorded illuminance levels, calculated illuminance values, KYTC lighting design standard compliance, and other attributes for each location ID.

ID Number	Maximum Illuminance	Minimum Illuminance	Average Illuminance	Uniformity Ratio	Minimum Illum (> 0.2)	Average Illum (> 0.8)	Uniformity Ratio < 4
1	3.34	0.30	1.29	11.13	Yes	Yes	No
2	7.69	0.12	2.11	63.03	No	Yes	No
3	3.67	0.11	1.14	33.06	No	Yes	No
4	2.51	0.42	1.08	6.02	Yes	Yes	No
5	2.85	0.31	1.38	9.28	Yes	Yes	No
6	1.21	0.02	0.33	60.50	No	No	No
7	1.21	0.04	0.37	30.25	No	No	No
8	1.05	0.08	0.52	13.13	No	No	No
9	1.11	0.11	0.54	10.09	No	No	No
10	1.58	0.04	0.63	39.50	No	No	No
11	1.69	0.05	0.53	33.80	No	No	No

Table 4: HPS Cobra Light Performance

ID Number	Light #1 Height	Light #2 Height	Light Spacing	Survey Spacing
1	UNK	UNK	257	25
2	28	29	200	20
3	29	29	200	20
4	29	28.5	135	13
5	28.5	28	122	12
6	31	31	242	24
7	31	31	221	22
8	29	29	158	15.5
9	29	29	145	14.5
10	30	30	200	20
11	30	30	198	20

Table 5: HPS Cobra Light Characteristics

Overall, HPS cobra lights demonstrated low compliance ratings with regard to KYTC lighting design standards. Minimum and average lighting illuminance levels met the standard for only 27.3 and 45.5 percent of surveyed sites. The minimum illuminance standard represents the lowest light level that properly illuminates the roadway surface under nighttime driving conditions. The average illuminance standard represents the sum of all the light measurements collected along a given pathway and divided by the total number of measurements. In both cases, positive compliance percentages indicated partial compliance with KYTC standards, with 100 percent representing full compliance. The last standard, the uniformity ratio, measures the variation between light levels along a given corridor. It is determined by dividing the maximum illuminance level by the minimum illuminance level along a measured pathway. This ratio should not exceed 4.0 per the KYTC policy. However, none of the surveyed HPS cobra light locations met the KYTC uniformity ratio standard. The full results for these conditions are shown in Tables 6-8 below.

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
11	0.15	0.2	-27.3%	3	8	27.3%

Table 6: HPS Cobra Lights, Minimum Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
11	0.90	0.80	12.7%	5	6	45.5%

Table 7: HPS Cobra Lights, Average Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
11	28.16	4.00	604.1%	0	11	0.0%

Table 8: HPS Cobra Lights, Uniformity Ratio

The research team also performed an in-depth analysis of minimum illuminance levels across the HPS cobra light locations. Minimum illuminance is considered a key factor in nighttime visibility for drivers. The analysis collected all minimum illuminance levels across all locations. Each light ID number (location) was associated with a single minimum illuminance light reading. For the HPS cobra lights, the research team collected eleven individual light readings for minimum illuminance corresponding to the eleven surveyed sites. Distances between minimum light levels and their closest light source were also required. Therefore, the team measured the horizontal distance from each minimum light reading location to the nearest corresponding roadside light source. Typically, a minimum illuminance light reading corresponded to the mid-way point between two adjacent roadside lights. Intuitively, this makes sense, as one would expect the light reading to be weakest at the point of greatest distance between two roadside lights placed in series. However, in some instances, the minimum illuminance reading was slightly closer to one light source than the other neighboring light source. This could be due to differences in light source characteristics such as wattage or the age of the light.

Prior to plotting these results, the research team assessed the data for conformity and reliability. A comprehensive examination of the eleven collected minimum illuminance readings revealed two sites with readings not consistent with the others. Light ID numbers 1 and 4 had meaningfully higher minimum illuminance recordings than all other HPS cobra light recordings. Upon further review, the research team discovered that both sites had external light interference stemming from external roadway light sources found on the opposite side of road. These additional lights impacted the light survey readings and made them less reliable. Therefore, these two sources were excluded from this analysis.

Finally, the research team used the validated data to plot minimum illuminance graphs across all surveyed sites. Each plot was graphed using the minimum light survey reading collected along a given measurement pathway (line 1). The y-axis displayed minimum illuminance readings while the x-axis displayed the horizontal distance between the surveyed illuminance location and its nearest adjacent light source. A best-fit line was plotted for each graph, resulting in an exponential trend line for each case. In each chart, the optimal spacing distance for two in-series HPS cobra lights (excluding outside light interference) may be found by tracing the minimum illuminance level of 0.20 foot-candles (y-axis) along the best-fit line to its corresponding distance (feet) on the x-axis. For midway points, the x-axis distance would be doubled to provide the total spacing required between two adjacent roadside lights. Graphs for all four pathways are shown below in Figures F-I.

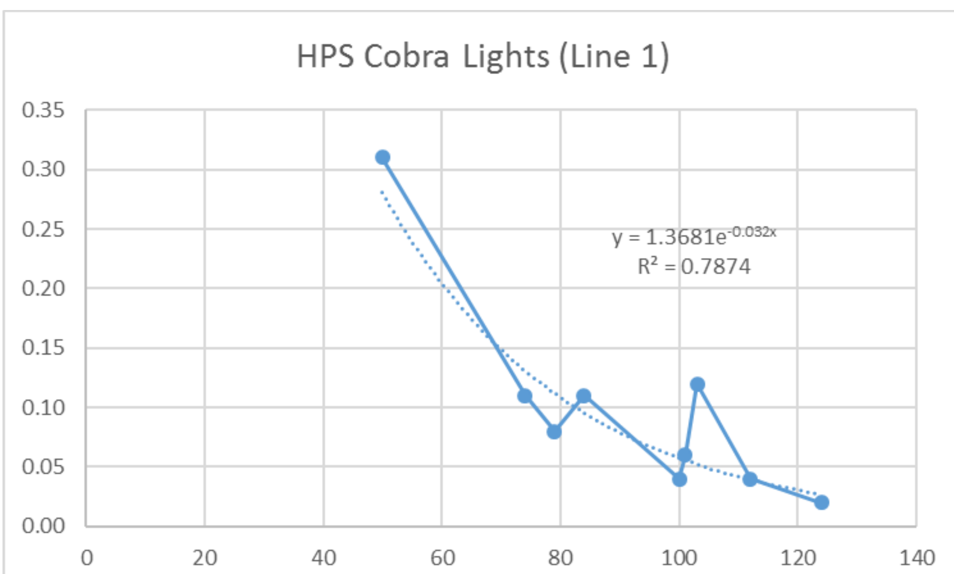


Figure F: HPS Cobra Lights, Minimum Illuminance along Line 1

X = 60 feet for minimum illuminance value of 0.20 foot-candles

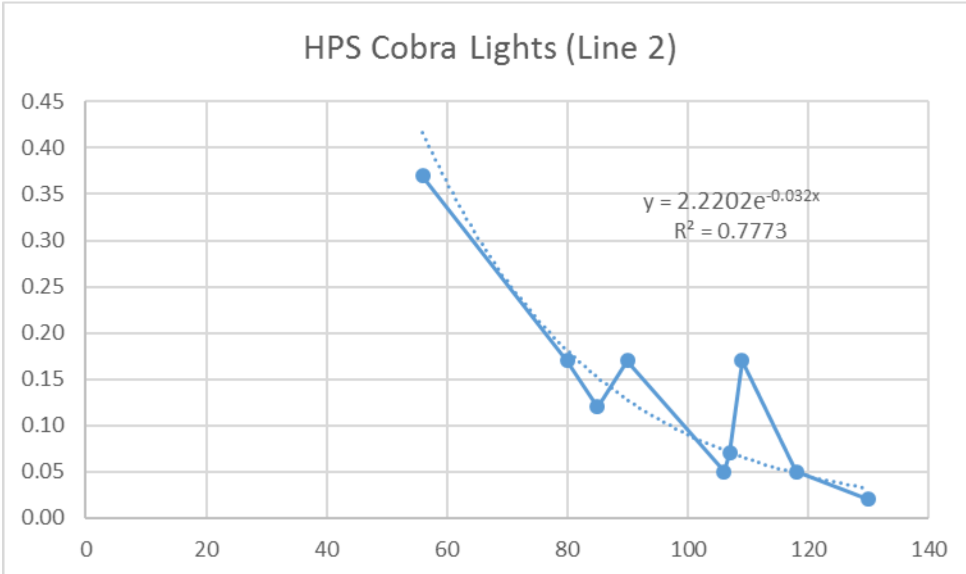


Figure G: HPS Cobra Lights, Minimum Illuminance along Line 2

X = 75 feet for minimum illuminance value of 0.20 foot-candles

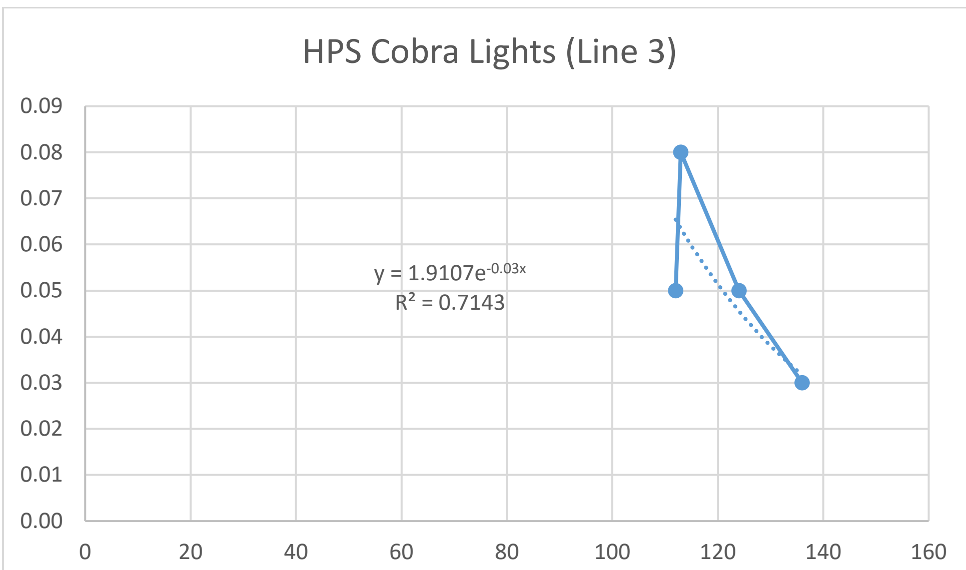


Figure H: HPS Cobra Lights, Minimum Illuminance along Line 3

X = 75 feet for minimum illuminance value of 0.20 foot-candles

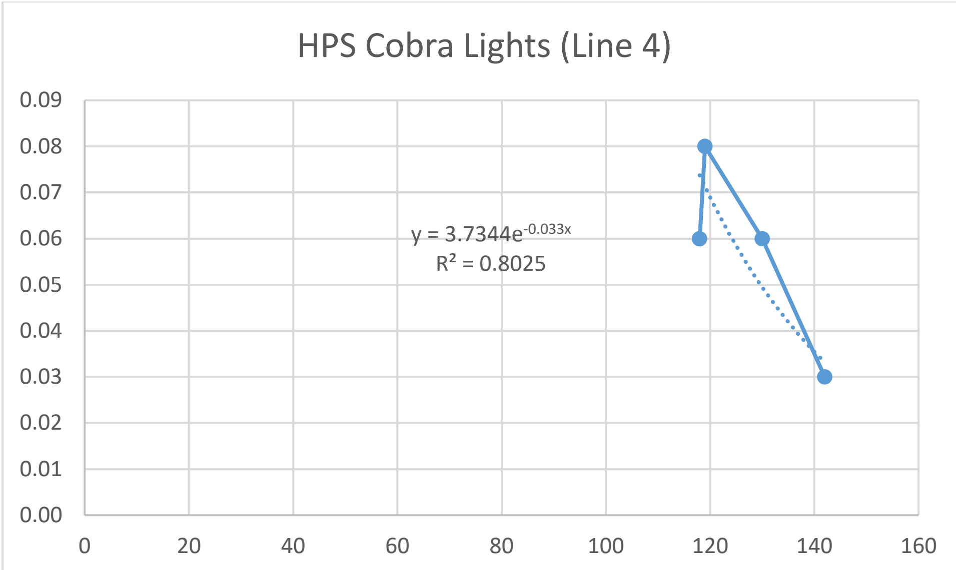


Figure I: HPS Cobra Lights, Minimum Illuminance along Line 4
X = 89 feet for minimum illuminance value of 0.20 foot-candles

The first two pathways required distances of 60 and 75 feet, respectively, to meet minimum illuminance levels. The second two pathways indicated levels were met at 75 and 89 feet, respectively. This data indicated that optimal light spacing should be between 120 to 180 feet for adjacent HPS cobra lights in the absence of other light sources.

In this analysis, the second two pathways had higher illuminance levels than expected. Further examination revealed that external light interference from an HPS cobra lights was occurring at light ID numbers 10 and 1 from on Interstate 71 near the Zorn Avenue ramp exit. This light source likely influenced readings along these surveyed segments and likely disproportionately influenced pathways #3 and #4 the most. This observation, along with limited readings overall for pathways #3 and #4, limits the ability to make inferences about HPS cobra lights installed on this second adjacent travel lane. Therefore, this analysis indicates a two-lane travel pathway should not place adjacent HPS cobra lights greater than 120 feet apart.

4.3.2 LED Cobra Lights

For LED cobra lights, the research team collected light measurements at eight roadside lighting locations. All cobra lights were considered conventional, but heights varied between 30 and 40 feet. This study treated all locations as conventional but recognized that elevated 40-foot height measurements may affect light survey readings. However, all surveyed LED cobra lights were used and treated as the same conventional heights within this study. Tables 9 and 10 provide the full results of the recorded illuminance levels and corresponding light attributes.

ID Number	Maximum Illuminance	Minimum Illuminance	Average Illuminance	Uniformity Ratio	Minimum Illum (> 0.2)	Average Illum (> 0.8)	Uniformity Ratio < 4
12	4.19	0.35	1.46	11.97	Yes	Yes	No
13	1.88	0.52	1.14	3.62	Yes	Yes	Yes
14	1.84	0.40	0.95	4.59	Yes	Yes	No
15	3.19	0.40	1.57	7.98	Yes	Yes	No
16	3.19	1.07	2.04	2.98	Yes	Yes	Yes
17	3.19	1.11	1.96	2.87	Yes	Yes	Yes
18	1.31	0.13	0.57	10.08	No	No	No
19	1.85	0.17	0.68	10.88	No	No	No

Table 9: LED Cobra Light Performance

ID Number	Light #1 Height	Light #2 Height	Light Spacing	Survey Spacing
12	UNK	UNK	300	25
13	30	30	146	15
14	30	30	185	18
15	39	40	254	25
16	40	40	95	9.5
17	40	40	98	9.5
18	30	30	168	17
19	30	30	172	17

Table 10: LED Cobra Light Characteristics

Across all three standards, the LED cobra lights had higher compliance percentages than the HPS cobra lights' compliance percentages. Minimum and average lighting illuminance levels frequently met KYTC design standards. In fact, each LED lighting attribute met KYTC requirements 75 percent of the time for the surveyed locations. Similarly, the uniformity ratio improved, compared to the HPS cobra light performance (at 0 percent), but still did not consistently meet KYTC design standards (at 37.5 percent). The full compliance results for surveyed locations are shown in Tables 11-13.

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
8	0.52	0.2	159.4%	6	2	75.0%

Table 11: LED Cobra Lights, Minimum Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
8	1.30	0.80	62.0%	6	2	75.0%

Table 12: LED Cobra Lights, Average Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
8	6.87	4.00	71.8%	3	5	37.5%

Table 13: LED Cobra Lights, Uniformity Ratio

Similar to HPS cobra lights, the research team examined LED cobra lights for minimum illuminance levels. This analysis used the same procedure as before by collecting all minimum illuminance levels at each light ID number, along with the distance from the survey reading to the nearest light source. Upon completion of the analysis, it was determined that ID numbers #12 and #15 had additional interference roadside lights on the opposite side from the light measurements. This interference impacted the light readings for the measured pathways and was therefore eliminated from the final analysis. All other locations and accompanying results were deemed satisfactory for further analysis.

With the final data, graphs were plotted for each measured pathway (line 1) with minimum illuminance levels on the y-axis and spacing to the nearest light on the x-axis. The best fit line was plotted for each graph, resulting in a linear trend line. The result makes sense since LED lights retain their illuminance over longer distances more uniformly than HPS lights (as demonstrated with their exponential loss patterns). In each plot, the optimal spacing distance may be found from the best fit line by tracing the minimum illuminance level of 0.20 foot-candles (y-axis) to its corresponding distance (feet) on the x-axis. The LED cobra light minimum illuminance charts are shown in the Figures J-M.

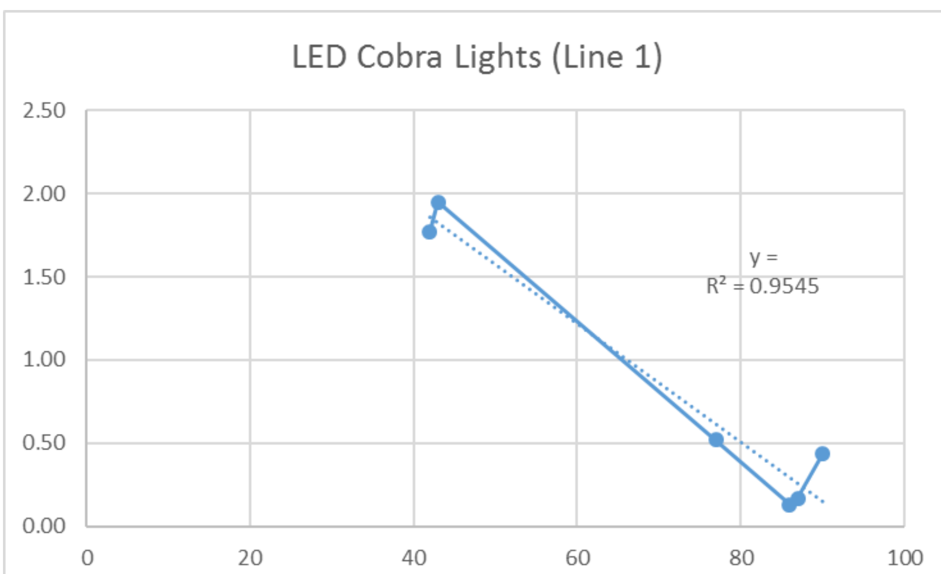


Figure J: LED Cobra Lights, Minimum Illuminance along Line 1

X = 89 feet for minimum illuminance value of 0.20 foot-candles

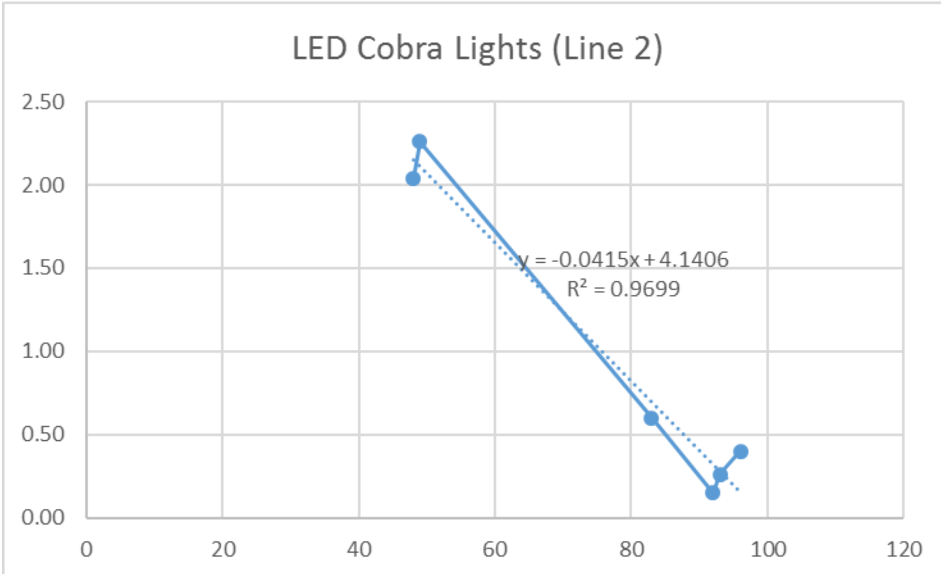


Figure K: LED Cobra Lights, Minimum Illuminance along Line 2

X = 95 feet for minimum illuminance value of 0.20 foot-candles

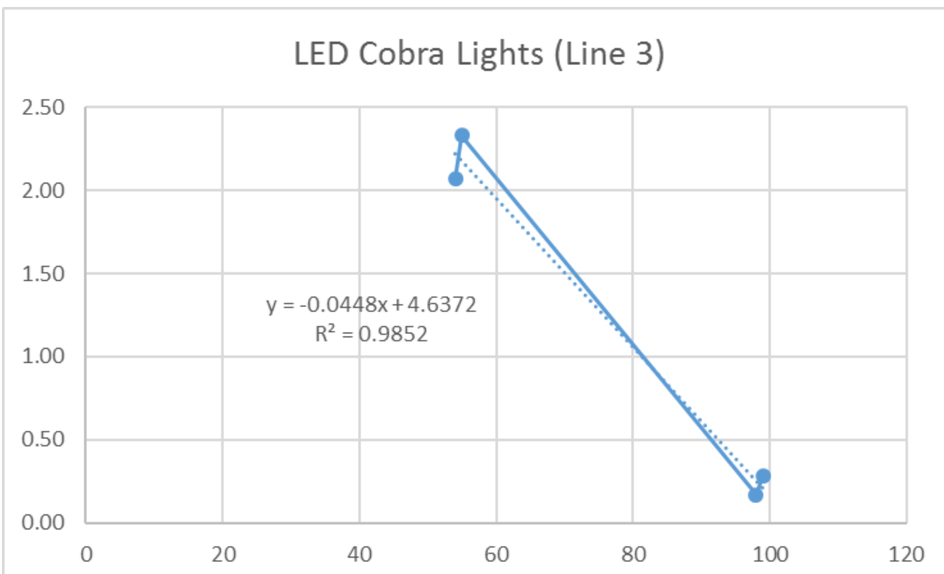


Figure L: LED Cobra Lights, Minimum Illuminance along Line 3

X = 99 feet for minimum illuminance value of 0.20 foot-candles

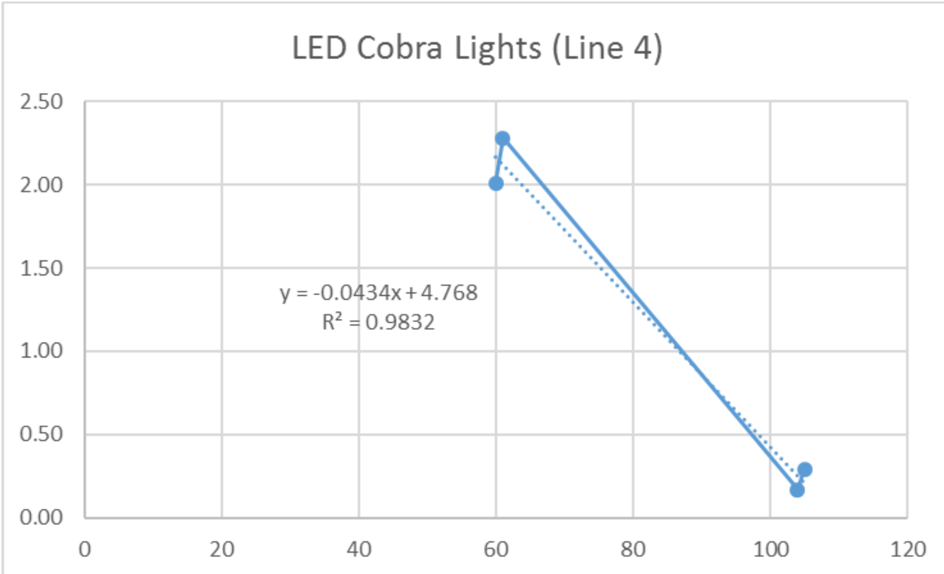


Figure M: LED Cobra Lights, Minimum Illuminance along Line 4
X = 105 feet for minimum illuminance value of 0.20 foot-candles

The first two pathways required distances of 89 and 95 feet, respectively, to meet minimum illuminance levels. The illuminance levels of the second two pathways were met at 99 and 105 feet. This data indicates that optimal light spacing should be between 178 and 210 feet for adjacent LED cobra lights in the absence of other light sources. This range exceeds the HPS cobra light optimal distances, which is characteristic of the increased output and consistency associated with LED lights. Due to the limited dataset available for pathways #3 and #4, researchers used caution when extrapolating recommendations for LED. Therefore, this analysis indicates a two-lane travel pathway should not place adjacent LED cobra lights greater than 178 feet apart.

4.3.3 HPS High-Mast Lights

High-mast roadside lights comprise approximately 25 percent of the overall KYTC roadside lighting inventory. The majority of these lights are located along the major interstates, including I-75, I-65, and I-64. The team collected a small sample size of high-mast light illuminance at three locations. Tables 14 and 15 illustrate the results from those surveyed locations.

ID Number	Maximum Illuminance	Minimum Illuminance	Average Illuminance	Uniformity Ratio	Minimum Illum (> 0.2)	Average Illum (> 0.8)	Uniformity Ratio < 4
20	3.31	0.15	1.04	22.07	No	Yes	No
21	2.06	0.18	0.93	11.44	No	Yes	No
22*	0.73	0.12	0.33	6.08	No	No	No
* Only a single HPS high-mast light in coverage area (so adjacent light not applicable)							

Table 14: HPS High-Mast Light Performance

ID Number	Light #1 Height	Light #2 Height	Light Spacing	Survey Spacing
20	120	120	1000	50
21	120	120	964	50
22	NA	NA	NA	25

Table 15: HPS High-Mast Light Characteristics

In summary, HPS high-mast lights performed poorly. None of the surveyed locations met minimum illuminance levels or uniformity ratios. Average illuminance levels met design standards at two of the three locations, as shown in Table 16, 17, and 18. Further analysis of optimal light spacing distance based on minimum illuminance levels was not conducted due to the limited number of readings for HPS high-mast lights.

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
3	0.15	0.2	-25.0%	0	3	0.0%

Table 16: HPS High-Mast Lights, Minimum Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
3	0.77	0.80	-4.2%	2	1	66.7%

Table 17: HPS High-Mast Lights, Average Illuminance

Total Sites (ID Number)	Average for all Readings	KYTC Standard	Percent Difference	Standard Attained (by Site)	Standard Unattained (by site)	Standard Compliance Percentage
3	13.20	4.00	230.0%	0	3	0.0%

Table 18: HPS High-Mast Lights, Uniformity Ratio

4.3.4 LED High-Mast Lights

Kentucky has only recently started installing LED high-mast lights across its road networks. At the time of this survey, only five such locations existed. The research team examined one location for this study, but due to the single sample point, additional surveys would be needed to confer any light compliance predictions. Nevertheless, the survey results and discussion are shown below.

ID Number	Maximum Illuminance	Minimum Illuminance	Average Illuminance	Uniformity Ratio	Minimum Illum (> 0.2)	Average Illum (> 0.8)	Uniformity Ratio < 4
23	2.98	0.30	1.41	9.93	Yes	Yes	No

Table 19: LED High-Mast Light Performance

ID Number	Light #1 Height	Light #2 Height	Light Spacing	Survey Spacing
23	141	127	750	50

Table 20: LED High-Mast Light Characteristics

Tables 19 and 20 illustrate that LED high-mast lights met both the minimum and average illuminance levels. However, they did not meet the uniformity ratio requirement. Further analysis of optimal light spacing distance based on minimum illuminance levels was not conducted due to the limited number of readings for LED high-mast lights.

4.4 Limitations of Survey Results

This research study was conducted as part of an in-service performance evaluation of roadside lights along state-maintained roads. Contrary to a controlled experiment, field studies gathered through light surveys during this research introduced realized and potential errors in data collection. The first limitation in this study was the size of the dataset. Project resource constraints imposed limitations on the number of locations that could be visited, and consequently limited the number of light surveys conducted. This is most evident for the high-mast roadside light locations.

Second, the research team was not able to collect roadside light heights for location ID numbers 1 and 12. These locations were assessed early during the study, and the laser distance measuring device was not yet available. Through visual observation, both light poles were estimated to be between 30 to 40 feet in height but an exact height was not available. Time constraints did not allow the research team to revisit this location later in the study and obtain the exact height.

Third, in some cases, minimum illuminance levels were found at unexpected longitudinal distances in survey readings across the line paths. Intuitively, minimum illuminance levels should be found at the furthest point from the two light sources along each survey path, or typically in the middle between the lights. This assumes no other outside light sources are located within the vicinity to cause light interference. Slight survey reading discrepancies may occur due to minor errors associated with hand-held readings. Typical errors may include: angle of light plane measurement, equipment tolerances, and spatial-temporal light output at any given moment (ensure shadow does not cover area).

Finally, external light sources within the nearby vicinity typically caused the largest errors in a few limited cases. Whenever possible, light segments were selected along a single roadside that was excluded from outside light source interference. However, this was not always possible as was the case with ID numbers 10 and 11 at the interchange of Interstate 71 and Zorn Avenue (subsequently excluded from the HPS cobra light pathway #3 and #4 analysis).

5. CONCLUSIONS

This research study examined the KYTC roadside lighting program across Kentucky to identify state-maintained inventory and to examine the performance of different lighting types. The roadside lights currently used in Kentucky include high-pressure sodium (HPS) and light-emitting diode (LED) lights. The KTC research team developed an accurate inventory of KYTC roadside lights and examined the performance differences of conventional and high-mast lighting. The findings and recommendations obtained from this study are described in the following sections.

5.1 Findings

- KYTC individual district offices are responsible for managing roadside lighting inventory across state-maintained roads but this information is not collected in a consistent format nor routinely shared with the Division of Traffic Operations.
- LED conventional lights routinely outperform HPS conventional lights in Kentucky across the following KYTC illuminance design standards:
    - Minimum illuminance (0.2 foot-candles): LED compliance (75.0%) to HPS compliance (27.3%)
    - Average illuminance (0.8 foot-candles): LED compliance (75.0%) to HPS compliance (45.5%)
    - Uniformity Ratio (4:1): LED compliance (37.5%) to HPS compliance (0.0%)
- LED conventional lights meet the KYTC minimum illuminance design standards at increased longitudinal light spacing of $\leq$ 178 feet, compared to HPS conventional lights spaced at $\leq$ 120 feet.
- LED high-mast lights appear to outperform HPS high-mast lights but a limited survey sample size impedes the validation of this hypothesis.

5.2 Recommendations

- Ensure KYTC district offices use a standard format when updating their roadside lighting inventory and share all updates with the Division of Traffic Operations in a timely manner.
- Continue KYTC roadside lighting programmatic efforts to transition from HPS to LED lights.
- Evaluate conventional longitudinal light spacing on new designs to meet KYTC minimum illuminance design standards.
- Conduct additional research to examine differences in high-mast light performance between LED and HPS lights.

6. APPENDIX A: ROADSIDE LIGHT DATA

6.1 HPS Cobra Lights

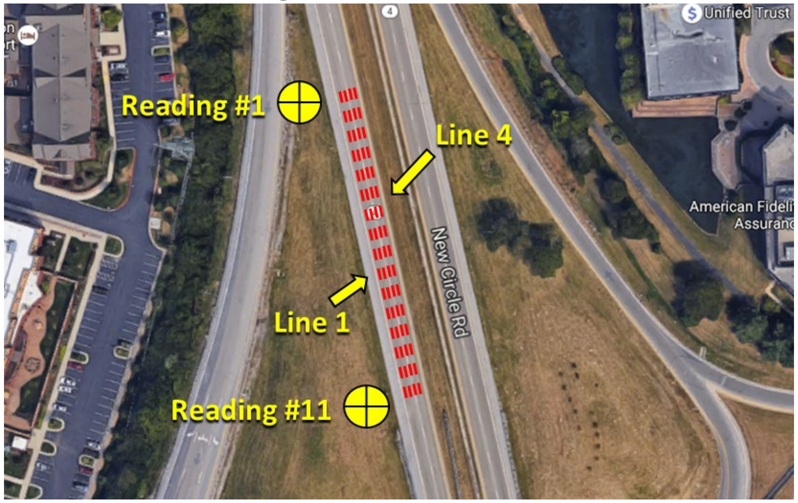


Figure N: Light ID #1 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	2.70	3.34	2.95	2.25
2	25	1.86	2.36	2.33	2.08
3	50	1.40	1.57	1.46	1.42
4	75	1.05	1.12	1.10	1.02
5	100	0.58	0.70	0.74	0.82
6	125	0.30	0.36	0.43	0.44
7	150	0.41	0.46	0.47	0.55
8	175	0.55	0.58	0.61	0.63
9	200	0.81	0.81	0.80	0.78
10	225	1.60	1.71	1.46	1.24
11	250	2.60	2.43	2.05	1.66

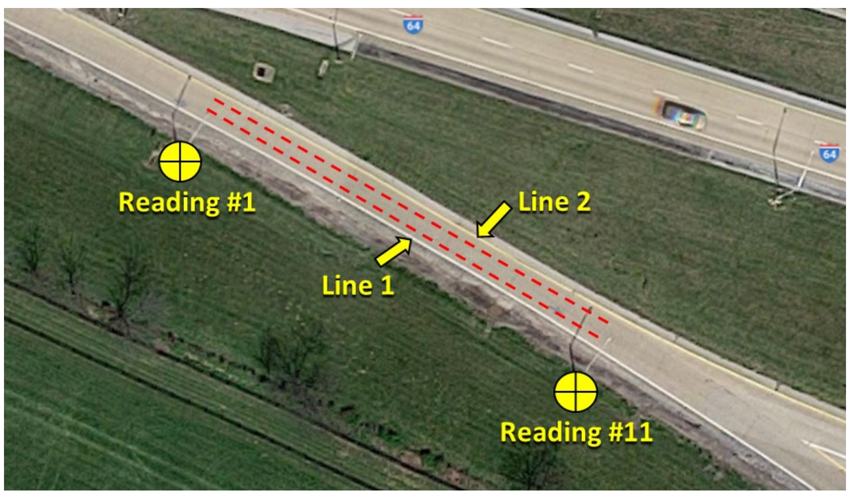
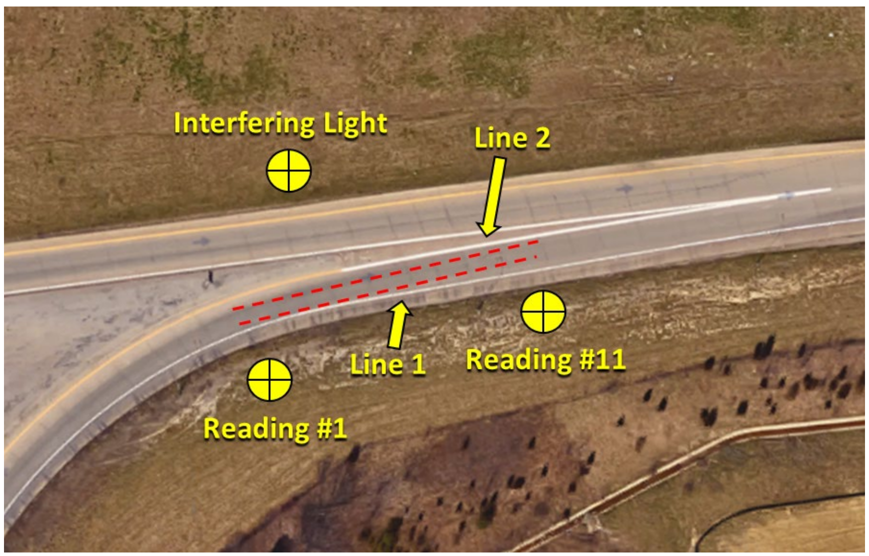


Figure O: Light #2 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	5.71	7.69
2	20	3.56	4.06
3	40	1.88	1.86
4	60	0.94	1.01
5	80	0.29	0.31
6	100	0.12	0.17
7	120	0.21	0.30
8	140	0.53	0.69
9	160	1.41	1.66
10	180	2.18	2.75
11	200	4.87	4.24

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	2.25	3.67
2	20	2.33	3.62
3	40	1.31	1.89
4	60	0.76	1.31
5	80	0.68	0.95
6	100	0.18	0.31
7	120	0.11	0.17
8	140	0.18	0.25
9	160	0.42	0.48
10	180	0.79	0.99
11	200	1.18	1.29

Figure P: Light ID #3 Map & Survey



Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	0.73	0.53
2	13	0.69	0.56
3	26	0.47	0.63
4	39	0.42	0.71
5	52	0.58	1.05
6	65	0.55	0.80
7	78	0.83	1.00
8	91	1.33	1.17
9	104	1.39	1.26
10	117	2.40	1.70
11	130	2.51	2.38

Figure Q: Light #4 Map & Survey

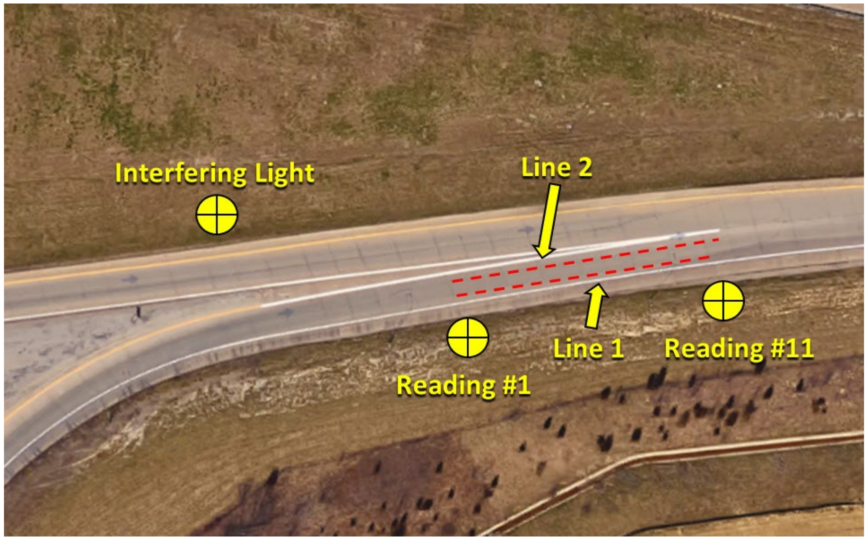


Figure R: Light #5 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	2.57	2.38
2	12	2.85	1.89
3	24	1.95	2.13
4	36	1.65	1.37
5	48	0.83	0.75
6	60	0.35	0.36
7	72	0.31	0.37
8	84	0.54	0.72
9	96	0.93	1.03
10	108	1.51	1.94
11	120	1.95	2.04

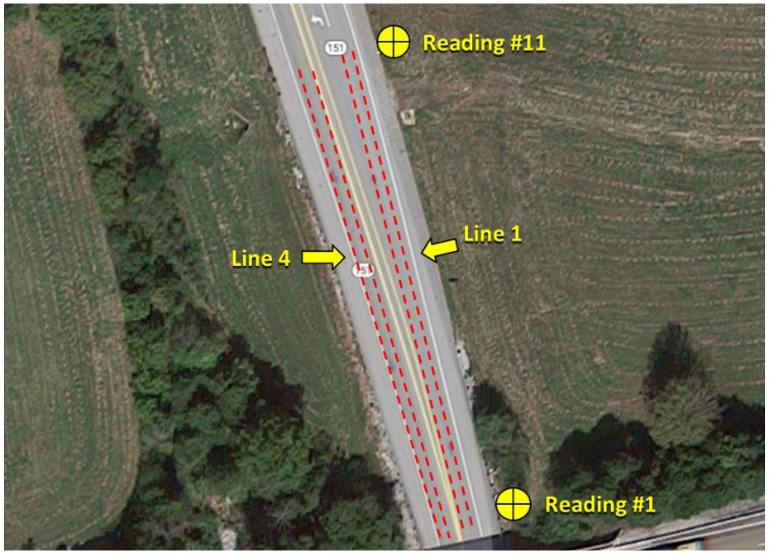


Figure S: Light #6 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	0.93	0.92	0.70	0.58
2	24	0.60	0.64	0.64	0.59
3	48	0.29	0.32	0.24	0.23
4	72	0.07	0.11	0.13	0.15
5	96	0.03	0.03	0.04	0.05
6	120	0.02	0.02	0.03	0.03
7	144	0.03	0.04	0.05	0.05
8	168	0.08	0.10	0.15	0.13
9	192	0.29	0.47	0.36	0.24
10	216	0.76	0.70	0.46	0.22
11	240	1.21	1.11	0.42	0.24

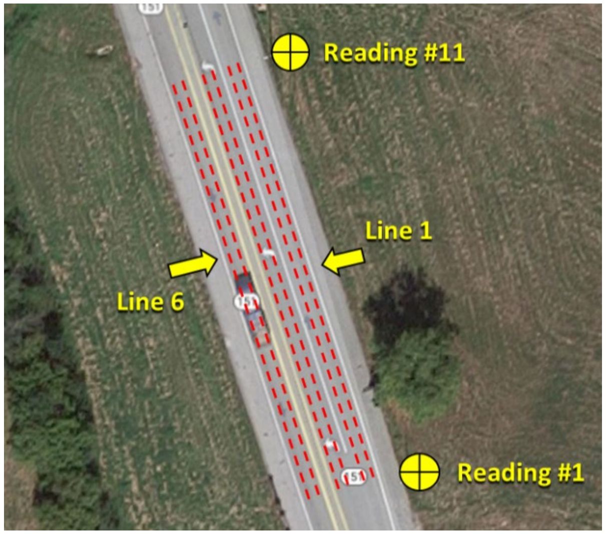


Figure T: Light #7 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)					
		Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
1	0	1.19	1.21	1.11	0.81	0.42	0.24
2	22	0.98	1.00	1.00	0.95	0.54	0.28
3	44	0.50	0.48	0.51	0.45	0.36	0.23
4	66	0.16	0.21	0.28	0.26	0.23	0.19
5	88	0.05	0.07	0.09	0.11	0.14	0.12
6	110	0.04	0.05	0.05	0.06	0.09	0.09
7	132	0.05	0.06	0.07	0.10	0.11	0.11
8	154	0.13	0.12	0.11	0.13	0.14	0.13
9	176	0.35	0.28	0.21	0.21	0.21	0.20
10	198	0.66	0.68	0.64	0.44	0.36	0.28
11	220	0.99	0.92	0.92	0.64	0.37	0.25

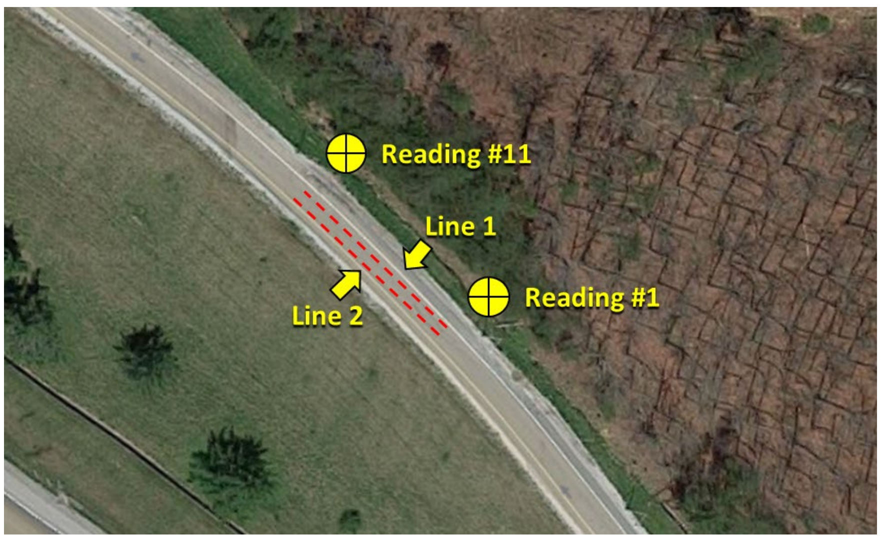


Figure U: Light #8 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	0.88	0.99
2	15.5	0.69	1.05
3	31	0.59	0.73
4	46.5	0.19	0.27
5	62	0.10	0.14
6	77.5	0.08	0.12
7	93	0.11	0.19
8	108.5	0.29	0.32
9	124	0.45	0.62
10	139.5	0.72	1.03
11	155	0.88	1.00

Figure V: Light #9 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	0.88	1.00
2	14.5	0.64	1.11
3	29	0.46	0.45
4	43.5	0.19	0.31
5	58	0.12	0.20
6	72.5	0.11	0.17
7	87	0.21	0.30
8	101.5	0.33	0.46
9	116	0.74	0.57
10	130.5	0.80	1.02
11	145	0.83	1.06

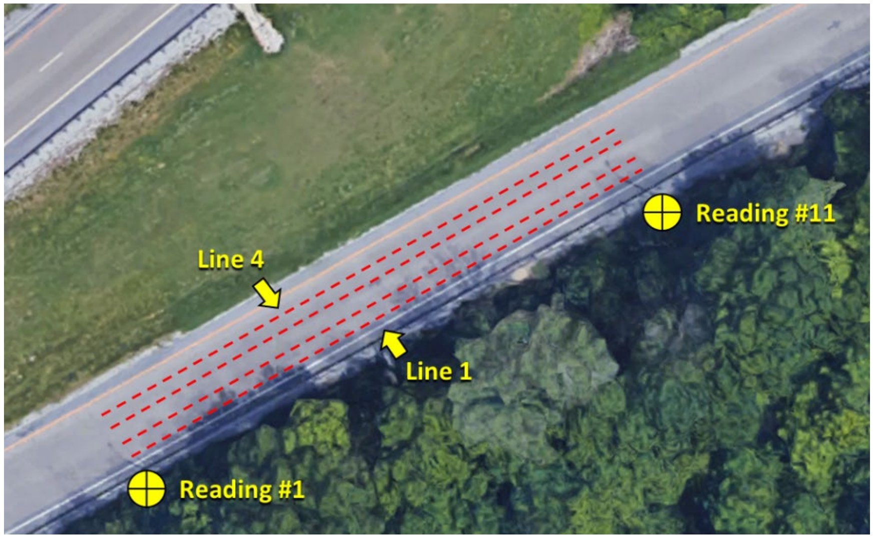


Figure W: Light #10 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	1.30	1.41	1.30	1.08
2	20	0.88	1.01	1.37	1.32
3	40	0.51	0.76	0.68	0.58
4	60	0.14	0.20	0.24	0.26
5	80	0.05	0.07	0.08	0.10
6	100	0.04	0.05	0.05	0.06
7	120	0.05	0.05	0.06	0.09
8	140	0.13	0.18	0.21	0.27
9	160	0.40	0.61	0.67	0.57
10	180	0.92	1.32	1.45	1.27
11	200	1.44	1.58	1.55	1.28

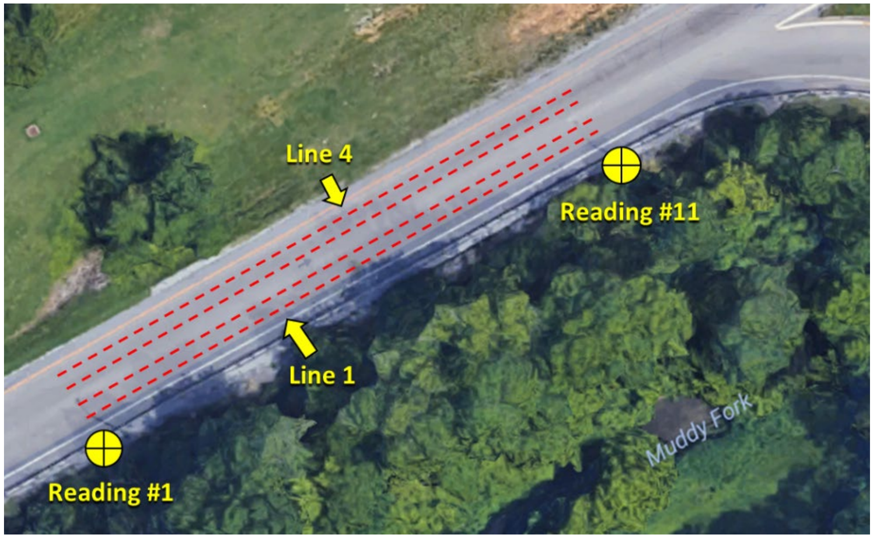


Figure X: Light #11 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	1.44	1.58	1.55	1.28
2	20	1.01	1.55	1.69	1.51
3	40	0.62	0.86	0.77	0.78
4	60	0.19	0.28	0.36	0.45
5	80	0.08	0.11	0.12	0.16
6	100	0.06	0.07	0.08	0.08
7	120	0.05	0.07	0.07	0.10
8	140	0.09	0.12	0.15	0.17
9	160	0.24	0.34	0.31	0.29
10	180	0.46	0.53	0.62	0.51
11	200	0.62	0.65	0.60	0.56

6.2 LED Cobra Lights

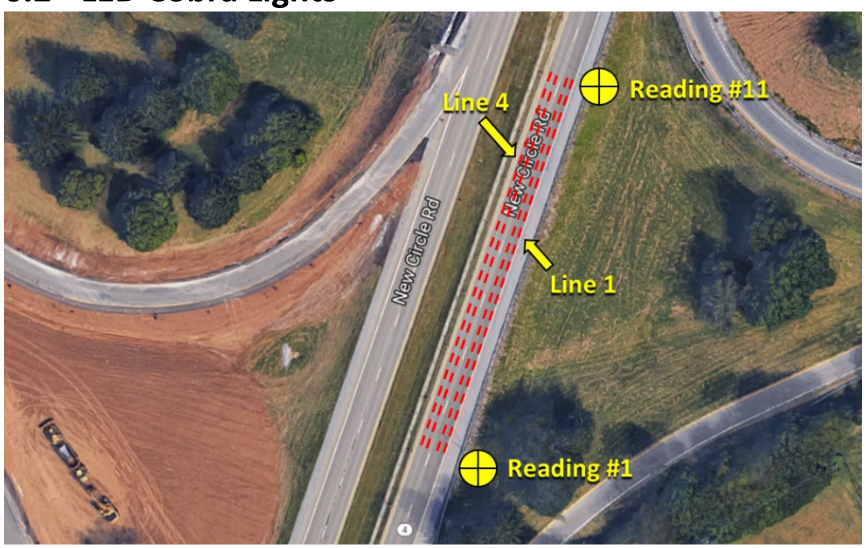


Figure Y: Light #12 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	4.19	3.82	3.29	3.34
2	30	2.98	2.80	2.47	2.34
3	60	1.89	1.93	1.91	1.84
4	90	1.40	1.45	1.62	1.49
5	120	1.00	1.11	1.23	1.32
6	150	0.56	0.56	0.67	0.80
7	180	0.35	0.44	0.58	0.69
8	210	0.38	0.44	0.44	0.54
9	240	0.55	0.73	0.76	0.77
10	270	0.87	0.92	1.13	1.11
11	300	1.98	1.87	1.75	1.84

Figure Z: Light #13 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	1.88	1.77
2	15	1.59	1.32
3	30	1.12	0.90
4	45	0.81	0.72
5	60	0.63	0.61
6	75	0.52	0.60
7	90	0.63	0.77
8	105	0.92	1.06
9	120	1.27	1.24
10	135	1.75	1.52
11	150	1.84	1.71

Figure AA: Light #14 Map & Survey

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	1.84	1.71
2	18	1.37	1.25
3	36	0.93	0.87
4	54	0.64	0.59
5	72	0.46	0.46
6	90	0.44	0.40
7	108	0.44	0.49
8	126	0.58	0.63
9	144	0.93	0.85
10	162	1.51	1.18
11	180	1.75	1.57

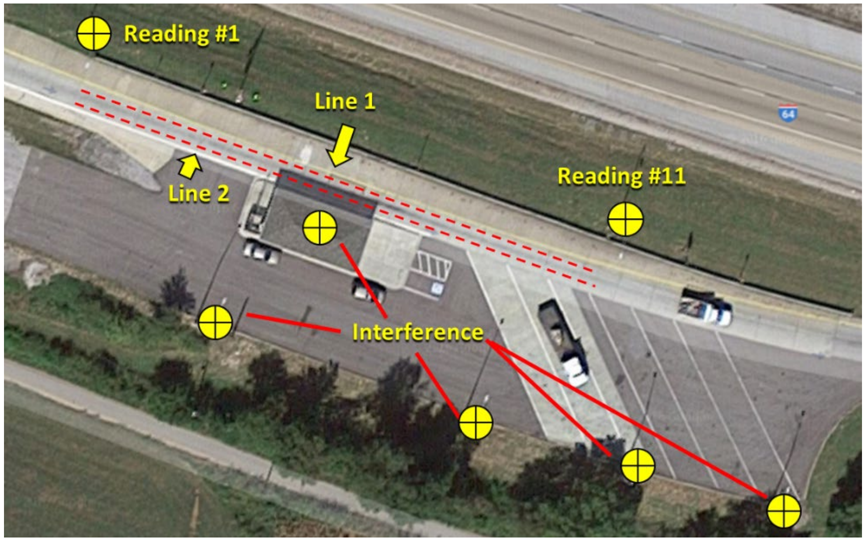
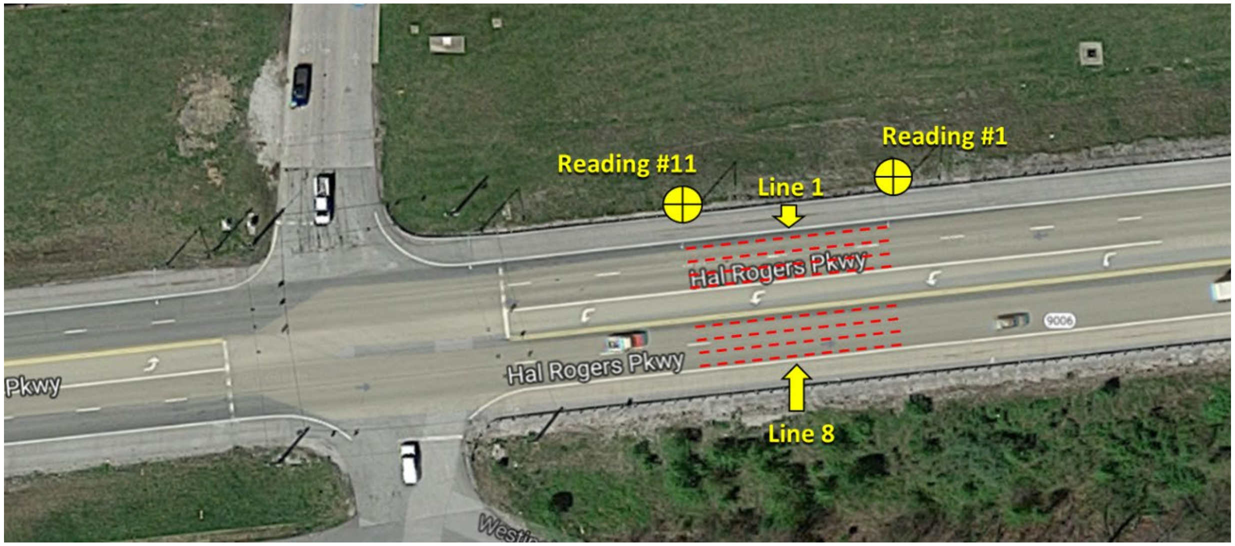


Figure BB: Light #15 Map & Survey

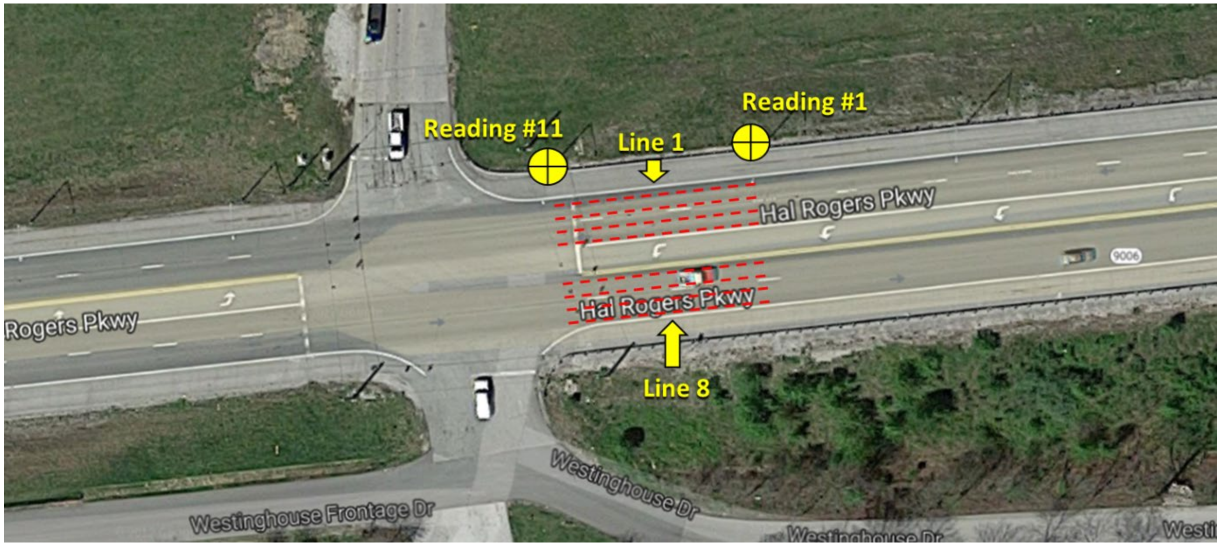
Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	2.72	2.52
2	25	2.12	1.93
3	50	1.49	1.50
4	75	1.13	1.19
5	100	0.98	1.05
6	125	0.40	0.45
7	150	0.68	0.74
8	175	1.02	1.18
9	200	1.56	1.67
10	225	2.38	1.97
11	250	3.19	2.63



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	2.60	2.61	2.50	2.41
2	9.5	2.56	2.63	2.56	2.43
3	19	2.22	2.50	2.46	2.42
4	28.5	2.01	2.32	2.33	2.37
5	38	1.95	2.26	2.33	2.28
6	47.5	2.06	2.32	2.35	2.31
7	57	2.07	2.34	2.40	2.31
8	66.5	2.18	2.50	2.53	2.47
9	76	2.32	2.73	2.71	2.60
10	85.5	2.73	3.07	3.01	2.75
11	95	2.98	3.19	3.07	2.79

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 5	Line 6	Line 7	Line 8
1	0	1.60	1.32	1.21	1.07
2	9.5	1.78	1.48	1.36	1.12
3	19	1.88	1.56	1.35	1.17
4	28.5	2.06	1.66	1.56	1.24
5	38	2.13	1.73	1.62	1.35
6	47.5	2.14	1.95	1.63	1.47
7	57	1.99	1.74	1.61	1.50
8	66.5	2.09	1.73	1.56	1.33
9	76	2.06	1.66	1.59	1.40
10	85.5	1.95	1.58	1.44	1.40
11	95	1.94	1.53	1.47	1.33

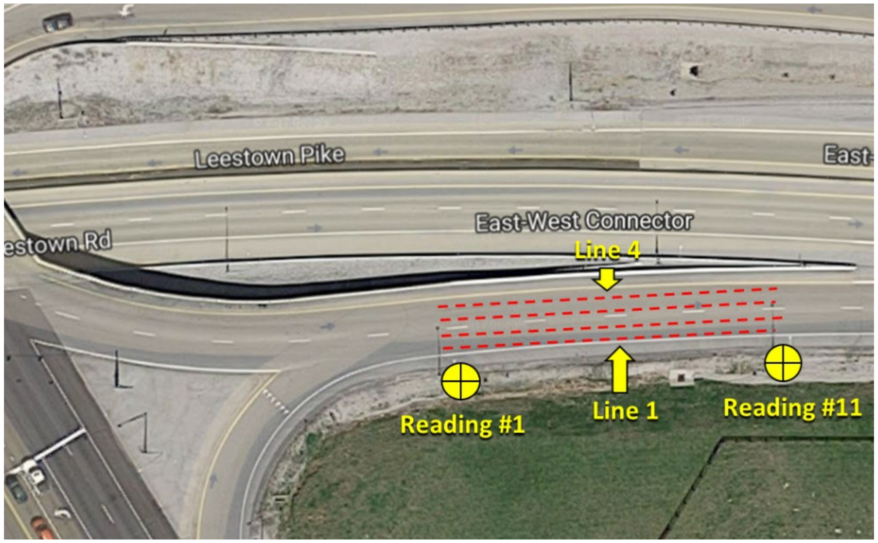
Figure CC: Light #16 Map & Survey



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	2.98	3.19	3.07	2.79
2	9.5	2.80	2.94	2.85	2.70
3	19	2.20	2.62	2.55	2.40
4	28.5	1.90	2.21	2.22	2.19
5	38	1.77	2.04	2.07	2.01
6	47.5	1.80	2.03	2.11	2.09
7	57	1.81	2.09	2.11	2.12
8	66.5	1.90	2.14	2.20	2.24
9	76	2.17	2.43	2.52	2.46
10	85.5	2.58	2.74	2.76	2.67
11	95	2.76	2.80	2.92	2.78

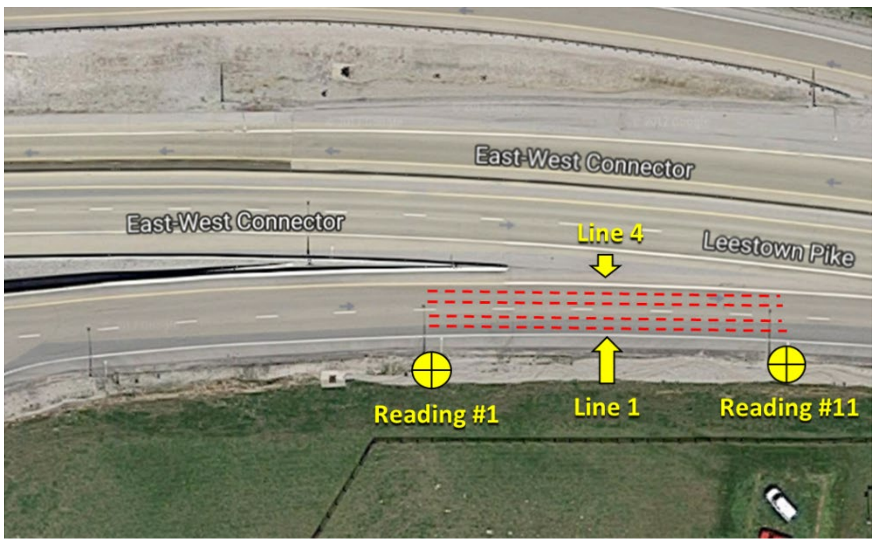
Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 5	Line 6	Line 7	Line 8
1	0	1.94	1.53	1.45	1.33
2	9.5	1.91	1.67	1.47	1.36
3	19	1.92	1.67	1.38	1.23
4	28.5	1.99	1.72	1.45	1.26
5	38	1.81	1.72	1.41	1.22
6	47.5	1.87	1.62	1.46	1.30
7	57	1.77	1.58	1.50	1.25
8	66.5	1.73	1.65	1.48	1.34
9	76	1.63	1.52	1.31	1.14
10	85.5	1.64	1.41	1.31	1.14
11	95	1.56	1.36	1.31	1.11

Figure DD: Light #17 Map & Survey



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	1.25	1.21	1.02	0.94
2	17	0.97	0.94	0.89	0.76
3	34	0.37	0.39	0.39	0.40
4	51	0.18	0.25	0.23	0.24
5	68	0.13	0.17	0.18	0.16
6	85	0.13	0.15	0.17	0.17
7	102	0.15	0.20	0.17	0.21
8	119	0.22	0.27	0.27	0.28
9	136	0.46	0.53	0.57	0.62
10	153	1.12	1.15	1.13	1.07
11	170	1.31	1.29	1.20	1.14

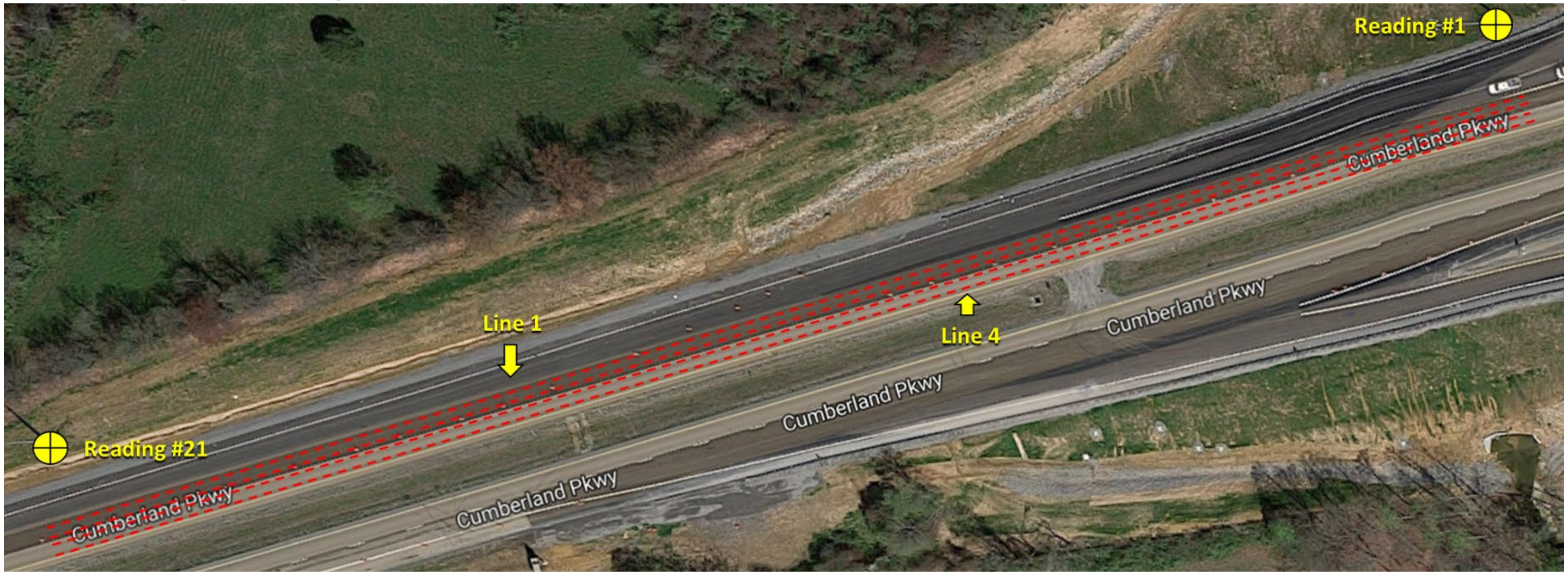
Figure EE: Light #18 Map & Survey



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	1.31	1.29	1.20	1.14
2	17	1.13	1.13	1.10	1.04
3	34	0.46	0.49	0.47	0.55
4	51	0.30	0.38	0.37	0.37
5	68	0.21	0.28	0.30	0.30
6	85	0.17	0.26	0.28	0.29
7	102	0.24	0.27	0.28	0.30
8	119	0.27	0.27	0.26	0.29
9	136	0.53	0.50	0.60	0.50
10	153	1.26	1.23	1.14	1.02
11	170	1.85	1.60	1.44	1.29

Figure FF: Light #19 Map & Survey

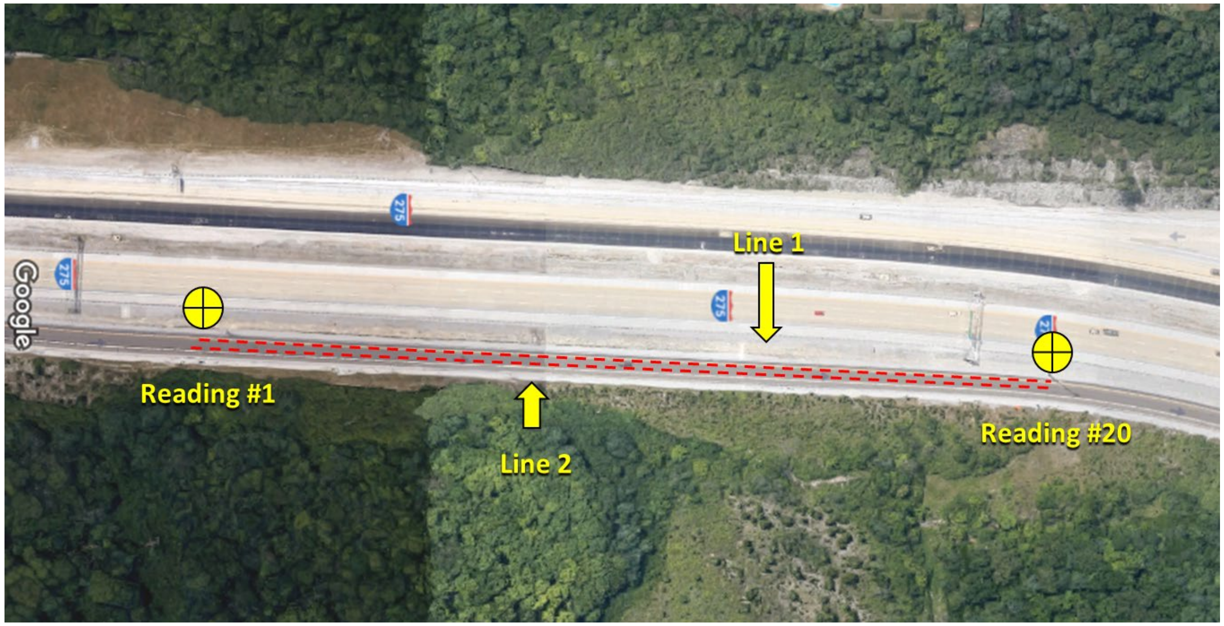
6.3 HPS High-Mast Lights



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	3.31	3.10	2.88	2.64
2	50	3.26	3.04	2.93	2.86
3	100	2.24	2.27	2.28	2.25
4	150	1.68	1.58	1.48	1.61
5	200	1.07	1.03	1.08	1.05
6	250	0.66	0.70	0.71	0.73
7	300	0.40	0.43	0.46	0.43
8	350	0.28	0.29	0.29	0.30
9	400	0.20	0.18	0.22	0.24
10	450	0.17	0.17	0.17	0.19
11	500	0.16	0.16	0.16	0.15

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
12	550	0.18	0.17	0.18	0.17
13	600	0.21	0.22	0.21	0.23
14	650	0.28	0.28	0.27	0.24
15	700	0.35	0.34	0.32	0.31
16	750	0.5	0.49	0.46	0.48
17	800	0.67	0.63	0.58	0.56
18	850	0.9	0.87	0.8	0.73
19	900	1.41	1.37	1.33	1.26
20	950	2.3	2.21	2.12	2.01
21	1000	2.76	2.56	2.48	2.32

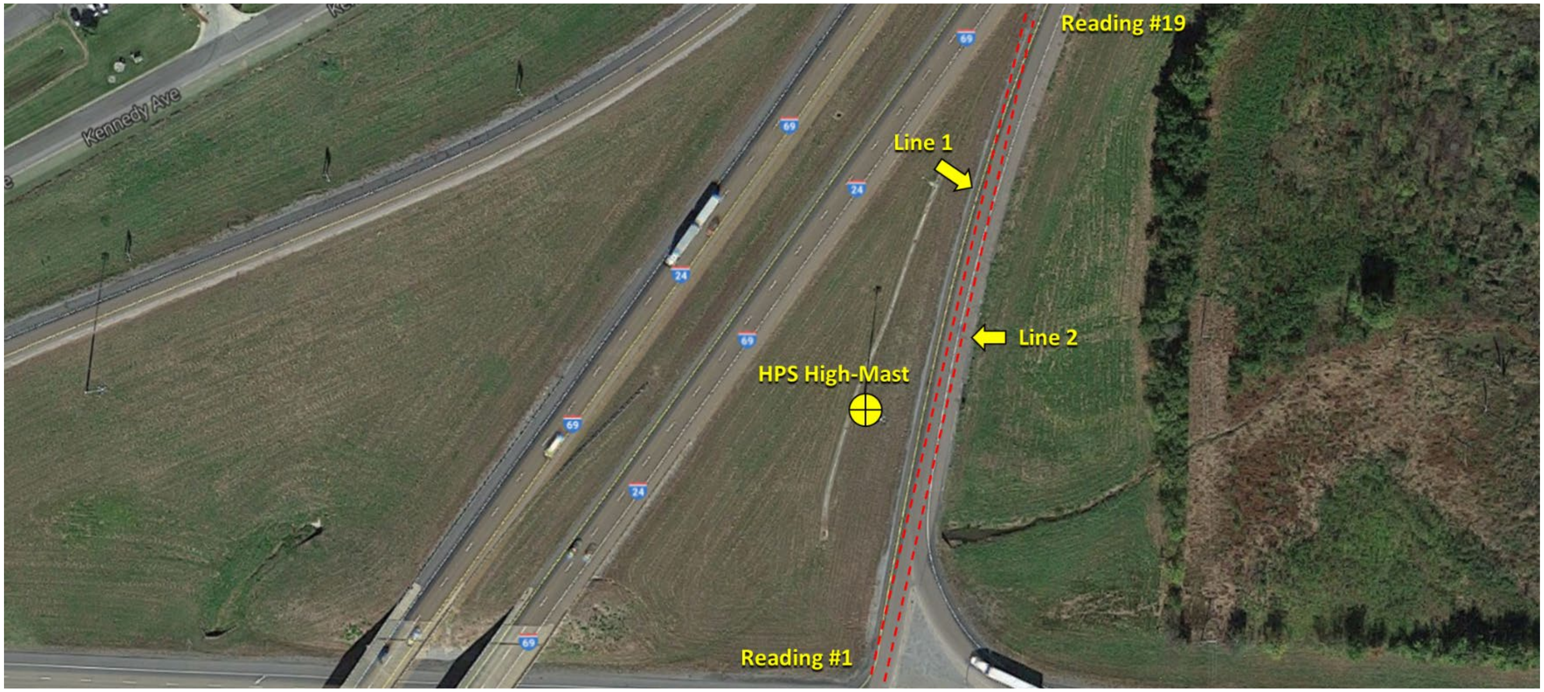
Figure GG: Light #20 Map & Survey



Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	1.89	2.00
2	50	2.06	1.95
3	100	1.25	1.14
4	150	1.04	0.87
5	200	0.81	0.72
6	250	0.52	0.46
7	300	0.38	0.34
8	350	0.24	0.23
9	400	0.20	0.20
10	450	0.19	0.18

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
11	500	0.19	0.21
12	550	0.27	0.25
13	600	0.33	0.34
14	650	0.62	0.53
15	700	0.85	0.86
16	750	1.37	1.21
17	800	1.78	1.65
18	850	1.73	1.48
19	900	1.71	2.01
20	950	1.65	1.68

Figure HH: Light #21 Map & Survey

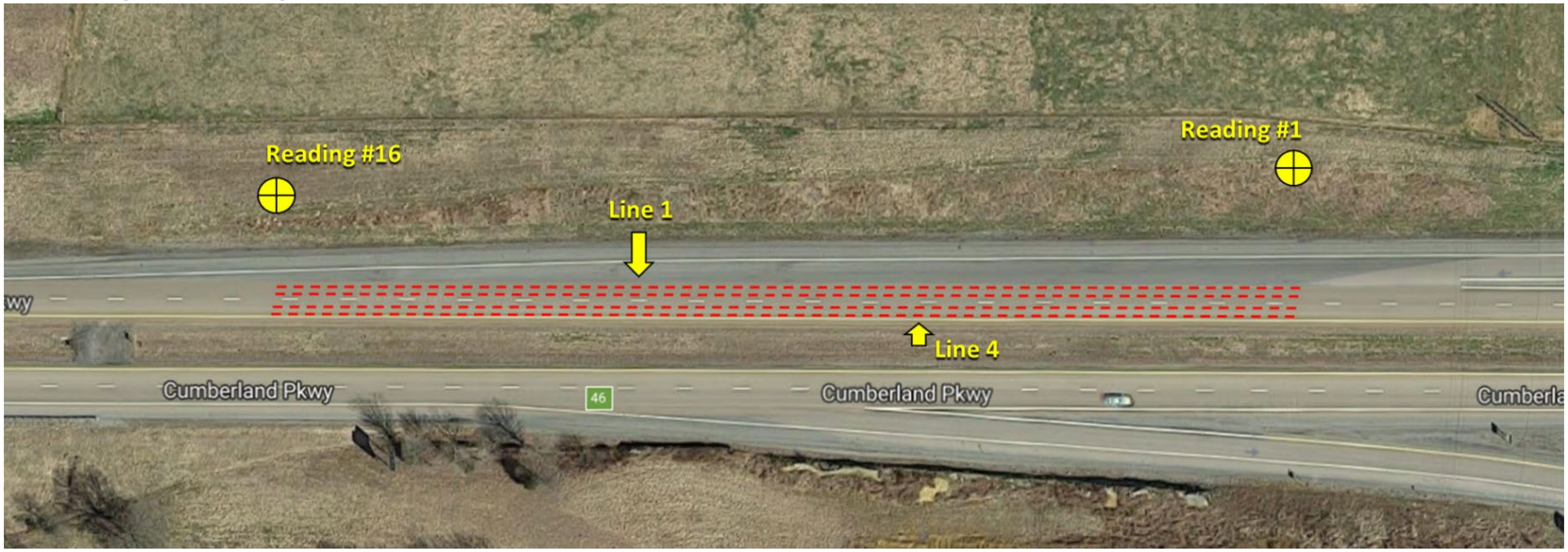


Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
1	0	0.16	0.13
2	25	0.16	0.12
3	50	0.18	0.14
4	75	0.17	0.15
5	100	0.19	0.17
6	125	0.23	0.26
7	150	0.36	0.32
8	175	0.44	0.39
9	200	0.62	0.48
10	225	0.73	0.56

Survey Reading	Distance (ft)	Illuminance (foot-candles)	
		Line 1	Line 2
11	250	0.70	0.53
12	275	0.60	0.48
13	300	0.49	0.41
14	325	0.41	0.37
15	350	0.36	0.33
16	375	0.29	0.26
17	400	0.26	0.24
18	425	0.25	0.22
19	450	0.18	0.19

Figure II: Light #22 Map & Survey

6.4 LED High-Mast Light



Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
1	0	2.25	2.27	2.30	2.29
2	50	2.35	2.32	2.22	2.11
3	100	1.99	1.93	1.79	1.74
4	150	1.20	1.19	1.18	1.15
5	200	0.79	0.78	0.75	0.76
6	250	0.51	0.51	0.52	0.55
7	300	0.35	0.36	0.35	0.35
8	350	0.31	0.31	0.30	0.30

Survey Reading	Distance (ft)	Illuminance (foot-candles)			
		Line 1	Line 2	Line 3	Line 4
9	400	0.35	0.34	0.34	0.32
10	450	0.48	0.49	0.49	0.46
11	500	0.74	0.72	0.75	0.73
12	550	1.18	1.22	1.11	1.08
13	600	1.88	1.83	1.77	1.67
14	650	2.88	2.91	2.73	2.67
15	700	2.77	2.92	2.93	2.98
16	750	2.56	2.82	2.9	2.95

Figure JJ: Light #23 Map & Survey

7. APPENDIX B: MINIMUM ILLUMINANCE LEVELS

* DTNL is the distance to the nearest light source at the given survey reading location (straight-line distance and not a longitudinal distance).

7.1 HPS Cobra Lights

ID Number	Line Number			
	1	1	2	2
	DTNL	Reading	DTNL	Reading
1	145	0.30	151	0.36
2	103	0.12	109	0.17
3	84	0.11	90	0.17
4	67	0.55	73	0.80
5	50	0.31	56	0.37
6	124	0.02	130	0.02
7	112	0.04	118	0.05
8	79	0.08	85	0.12
9	74	0.11	80	0.17
10	100	0.04	106	0.05
11	101	0.06	107	0.07

Table 21: HPS Cobra Lights, Line Numbers #1 & #2

ID Number	Line Number			
	3	3	4	4
	DTNL	Reading	DTNL	Reading
1	157	0.43	163	0.44
2				
3				
4				
5				
6	136	0.03	142	0.03
7	124	0.05	130	0.06
8				
9				
10	112	0.05	118	0.06
11	113	0.08	119	0.08

Table 22: HPS Cobra Lights, Line Numbers #3 & #4

ID Number	Line Number			
	5	5	6	6
	DTNL	Reading	DTNL	Reading
1				
2				
3				
4				
5				
6				
7	136	0.09	142	0.09
8				
9				
10				
11				

Table 23: HPS Cobra Lights, Line Numbers #5 & #6

7.2 LED Cobra Lights

ID Number	Line Number			
	1	1	2	2
	DTNL	Reading	DTNL	Reading
12	122	0.35	128	0.44
13	77	0.52	83	0.60
14	90	0.44	96	0.40
15	126	0.40	132	0.45
16	43	1.95	49	2.26
17	42	1.77	48	2.04
18	86	0.13	92	0.15
19	87	0.17	93	0.26

Table 24: LED Cobra Lights, Line Numbers #1 & #3

ID Number	Line Number			
	3	3	4	4
	DTNL	Reading	DTNL	Reading
12	94	0.44	100	0.54
13				
14				
15				
16	55	2.33	61	2.28
17	54	2.07	60	2.01
18	98	0.17	104	0.17
19	99	0.28	105	0.29

Table 25: LED Cobra Lights, Line Numbers #3 & #4

ID Number	Line Number			
	5	5	6	6
	DTNL	Reading	DTNL	Reading
12				
13				
14				
15				
16	57	1.60	63	1.32
17	57	1.56	63	1.36
18				
19				

Table 26: LED Cobra Lights, Line Numbers #5 & #6

ID Number	Line Number			
	7	7	8	8
	DTNL	Reading	DTNL	Reading
12				
13				
14				
15				
16	69	1.21	75	1.07
17	69	1.31	75	1.11
18				
19				

Table 27: LED Cobra Lights, Line Numbers #7 & #8

8. APPENDIX C: LIGHT ID PROFILES

8.1 HPS Cobra Lights

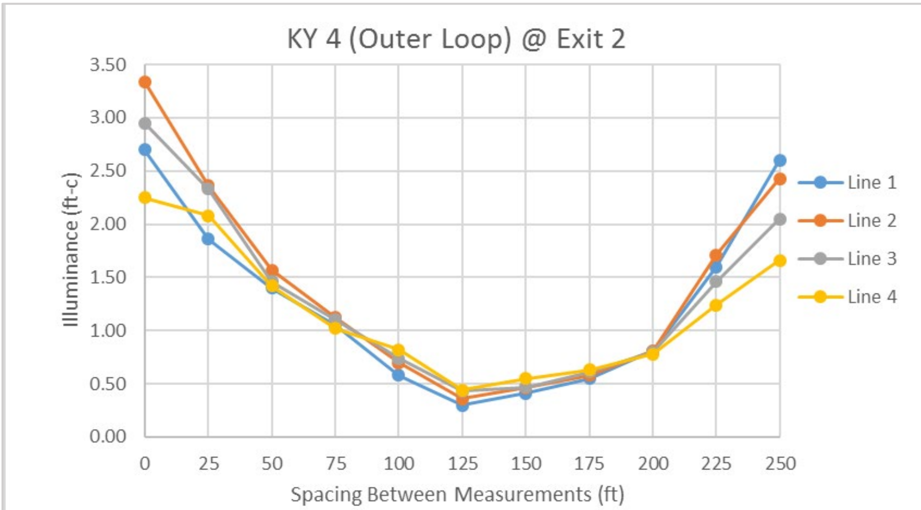


Figure KK: Light ID #1 Profile

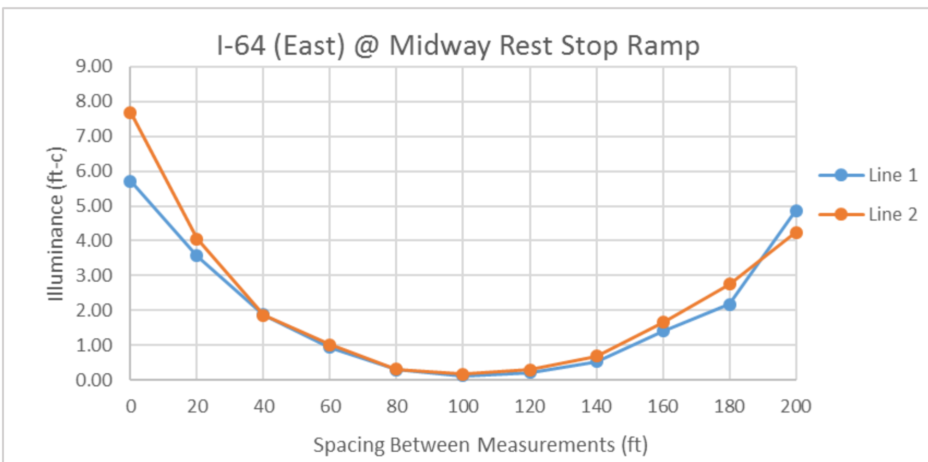


Figure LL: Light ID #2 Profile

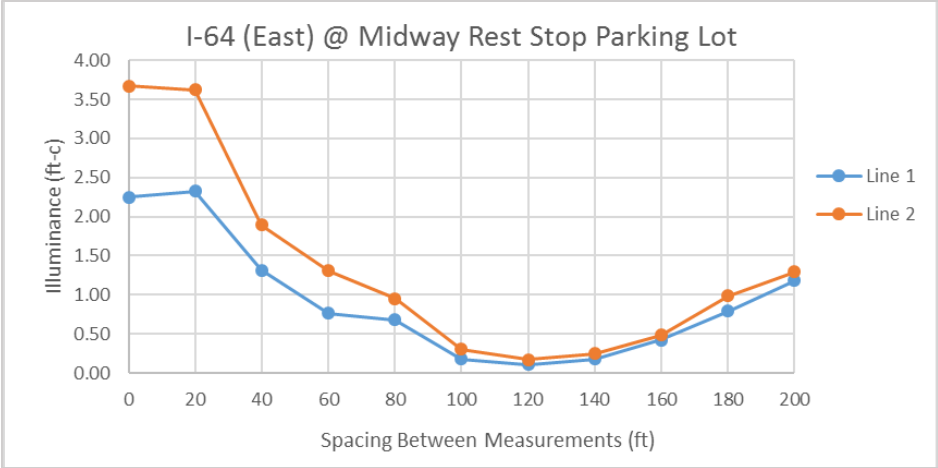


Figure MM: Light ID #3 Profile

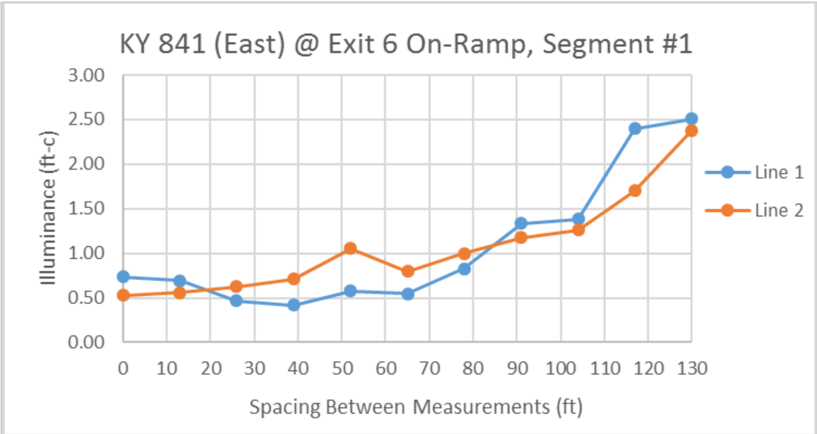


Figure NN: Light ID #4 Profile

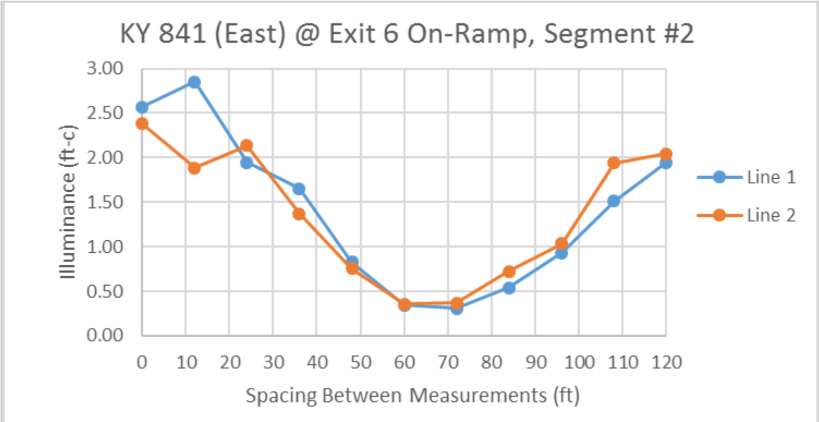


Figure OO: Light ID #5 Profile

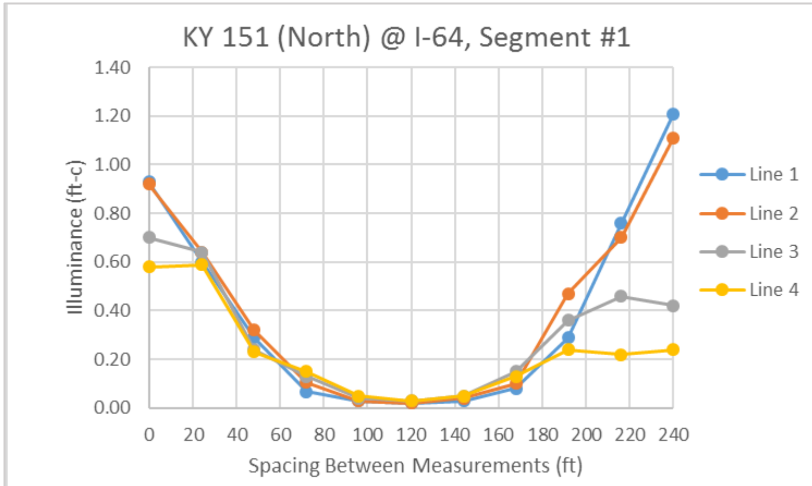


Figure PP: Light ID #6 Profile

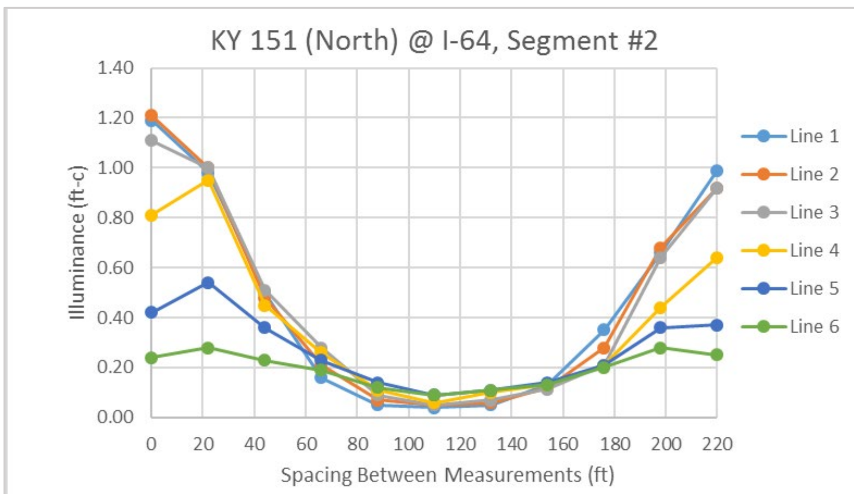


Figure QQ: Light ID #7 Profile

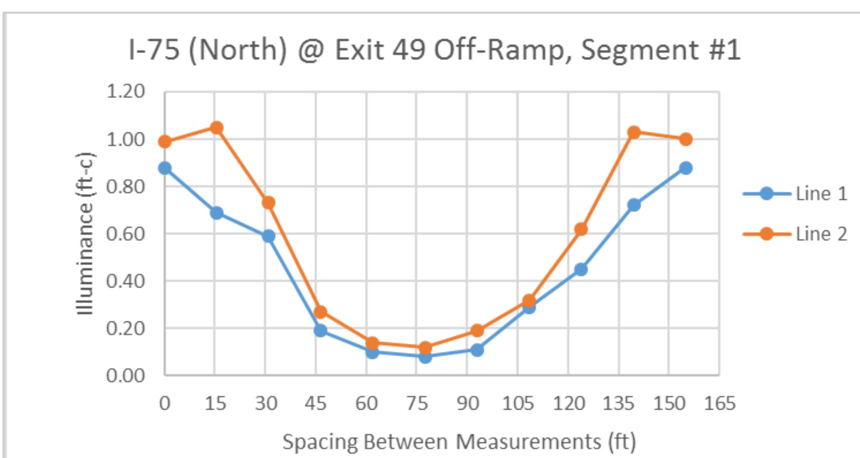


Figure RR: Light ID #8 Profile

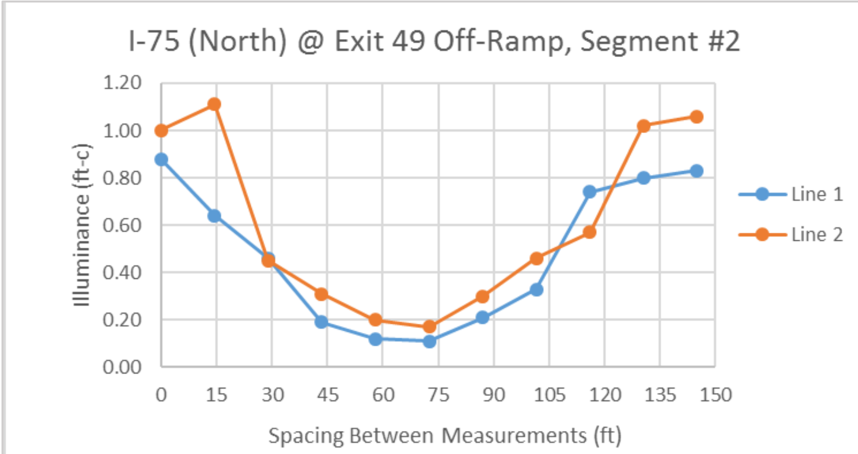


Figure SS: Light ID #9 Profile

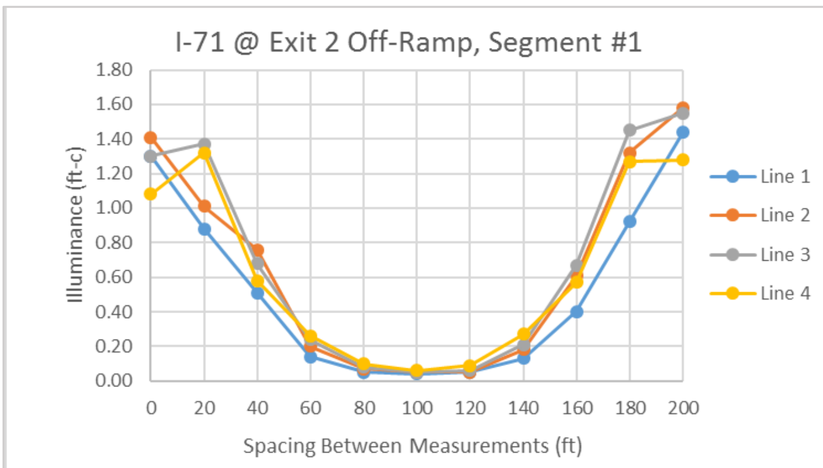


Figure TT: Light ID #10 Profile

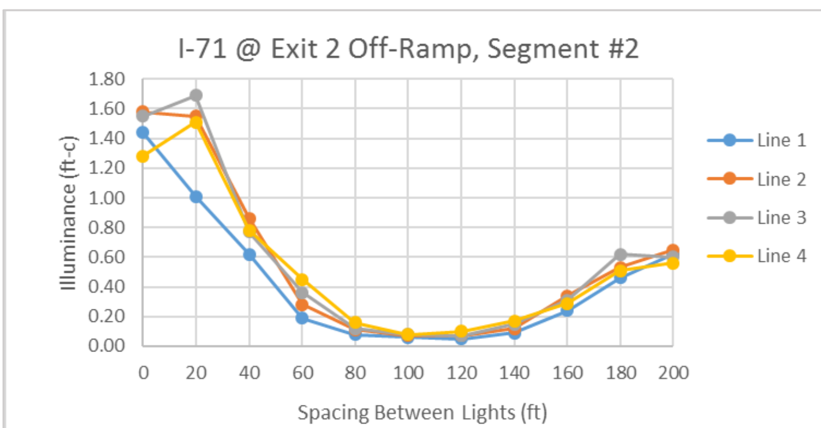


Figure UU: Light ID #11 Profile

8.2 LED Cobra Lights

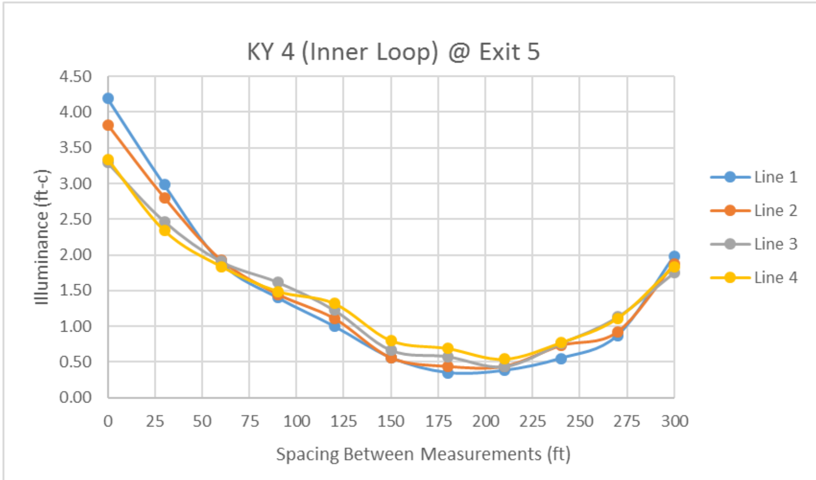


Figure VV: Light ID #12 Profile

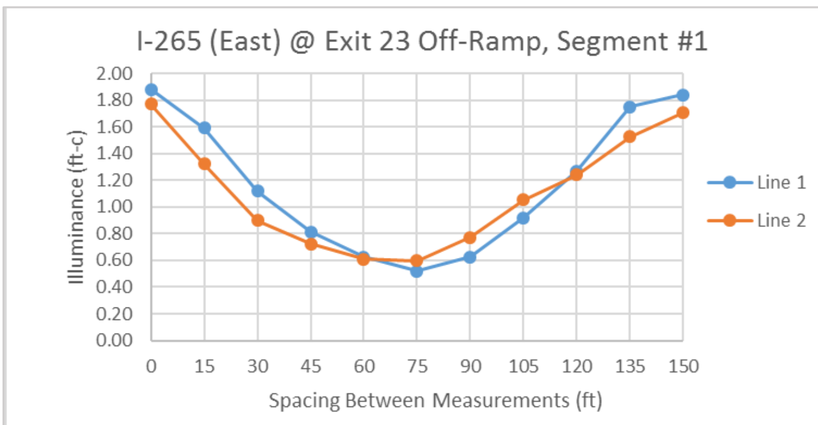


Figure WW: Light ID #13 Profile

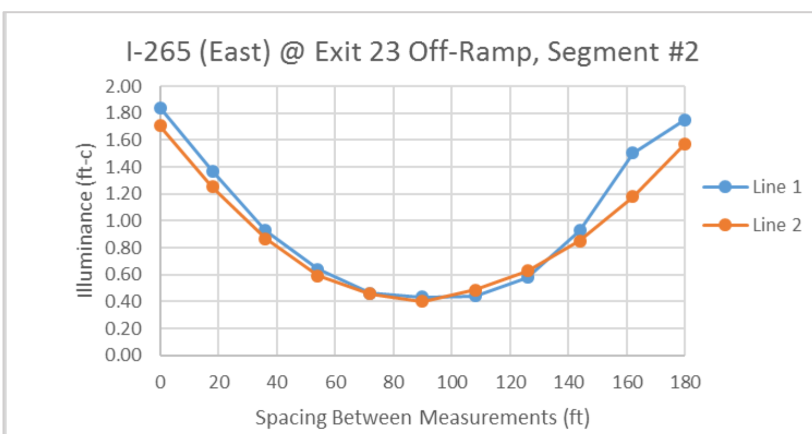


Figure XX: Light ID #14 Profile

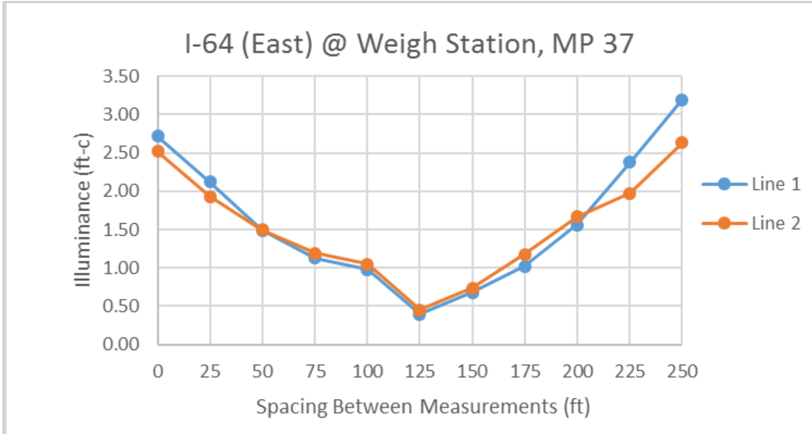


Figure YY: Light ID #15 Profile

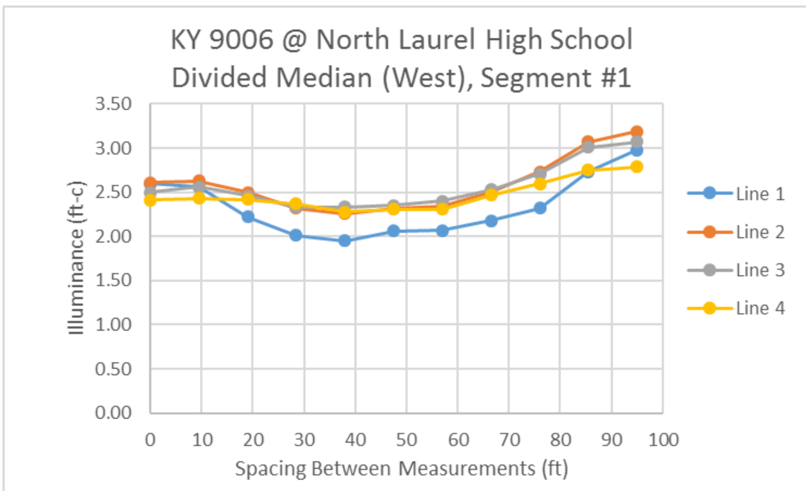


Figure ZZ: Light ID #16a Profile (WB)

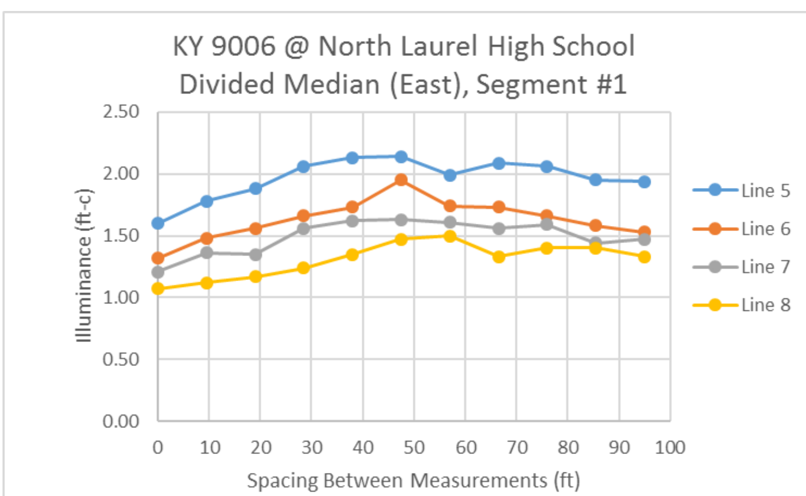


Figure AAA: Light ID #16b Profile (EB)

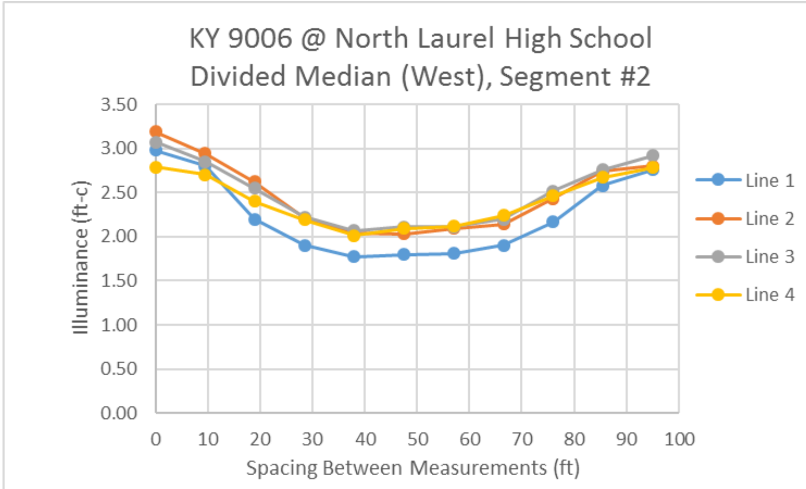


Figure BBB: Light ID #17a Profile (WB)

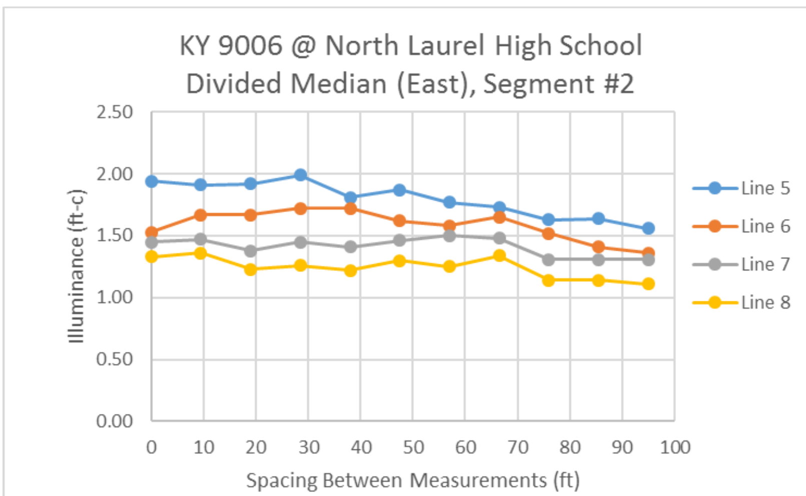


Figure CCC: Light ID #17b Profile (EB)

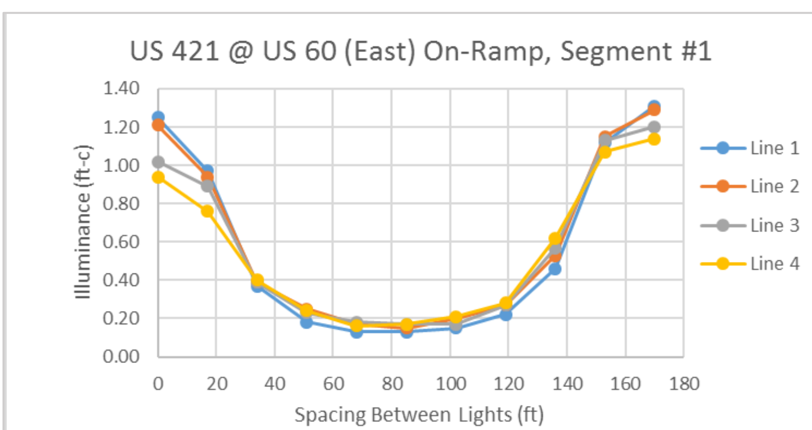


Figure DDD: Light ID #18 Profile

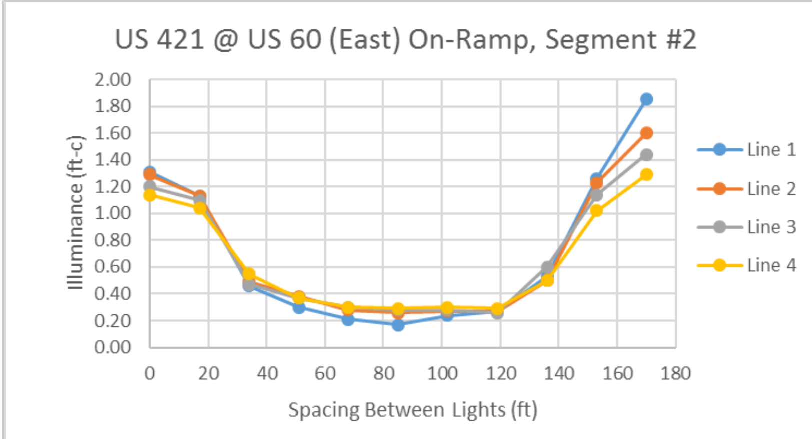


Figure EEE: Light ID #19 Profile

8.3 HPS High-Mast Lights

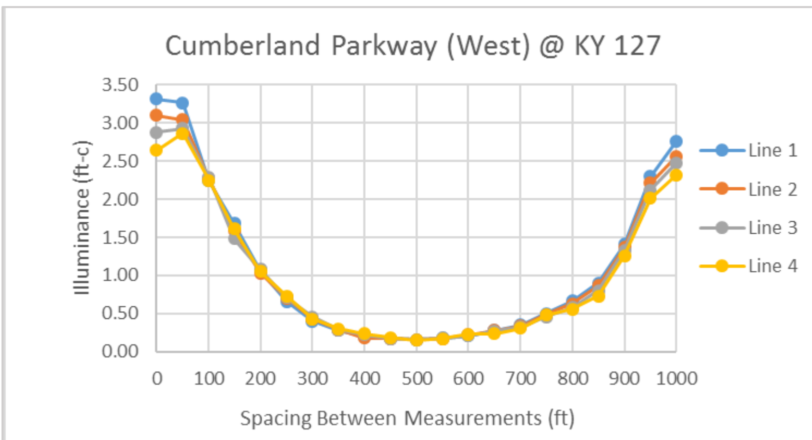


Figure FFF: Light ID #20 Profile

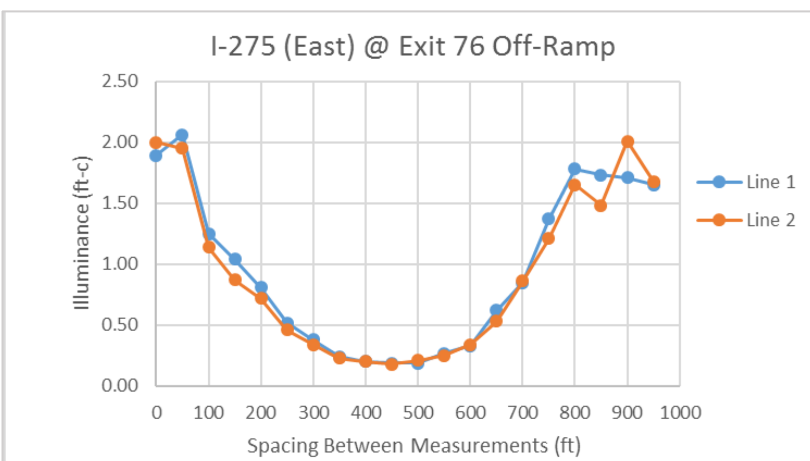


Figure GGG: Light ID #21 Profile

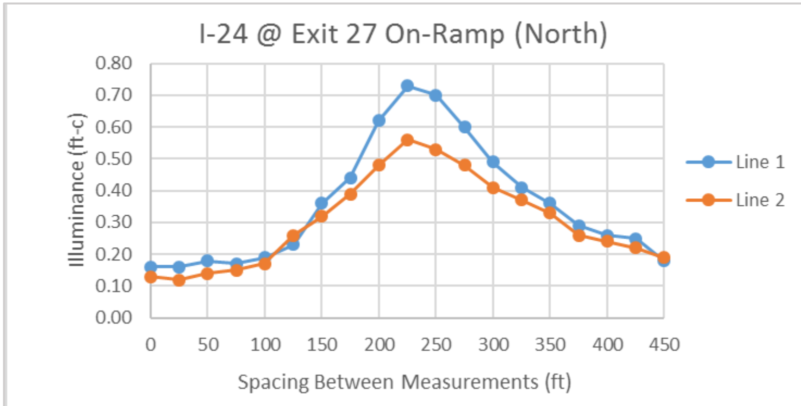


Figure HHH: Light ID #22 Profile

8.4 LED High-Mast Lights

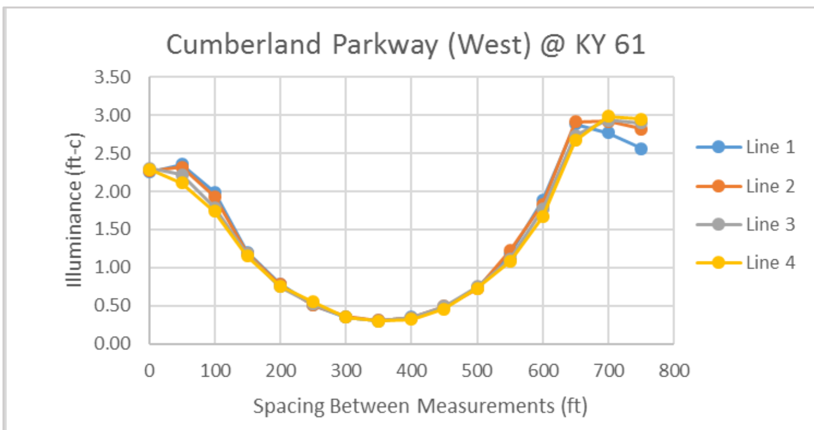


Figure III: Light ID #23 Profile

9. References

[1] American Association of State and Highway Transportation Officials (AASHTO). "Highway Safety Manual." Washington, D.C. 2010.

[2] American Association of State and Highway Transportation Officials (AASHTO). "Roadway Lighting Design Guide." December 2005.

[3] Illuminating Engineering Society (IES). "Roadway Lighting." ANSI/IES RP-8-14. June 2014.

[4] Lutkevich, P.; McLean, D.; and Cheung, J. "FHWA Lighting Handbook." Parsons Brinckerhoff, 2012.

[5] TAC, Guide for the Design of Roadway Lighting, Transportation Association of Canada Volume 1 – Fundamentals and Volume 2 – Design, January 2006.

[6] CTC & Associates LLC. "Highway Lighting Practices and Policies, CalTrans Division of Traffic Operations." October 2013.

[7] Cai, Hongyi, Ph.D., University of Kansas, Department of Civil Engineering. "Kansas Highway LED Illumination Manual: A Guide for the Use of LED Lighting Systems." December 2015.

[8] Bullough, J.; Skinner, N.; and Brons, J., Lighting Research Center at the Rensselaer Polytechnic Institute. "Analysis of Energy Efficient Highway Lighting Retrofits." New York State Department of Transportation. June 2015.

[9] Li, Shou Et al. "Cost- and Energy-Efficient (LED, Induction, and Plasma) Roadway Lighting." Joint Transportation Research Program: Indiana DOT and Purdue University (2013). FHWA/IN/JTRP-2013/19.

[10] Gibbons, Ronald B., et al. "Design criteria for adaptive roadway lighting." No. FHWA-HRT-14-051. United States. Federal Highway Administration, 2014.

[11] Washington State DOT. "LED Adaptive lighting and illumination reform." October 2013. Obtained from: https://www.wsdot.wa.gov/sites/default/files/2017/08/10/PracSol-LEDAdaptiveLightingIllumReform.pdf

[12] Quick, S., et al. "LED Street Light Research Project Part II: New Findings." Remaking Cities Institute. Carnegie Mellon University and the City of Pittsburgh. May 2016.

[13] Kentucky Transportation Cabinet. "Traffic Operations Guidance Manual." June 2005 with 2015 updates.

[14] https://sensing.konicaminolta.us/products/t-10-t-10m-illuminance-meters/, Obtained on July 30, 2018.

[15] https://www.boschtools.com/us/en/boschtools-ocs/laser-measuring-glm-80-34662-p/, Obtained on August 1, 2018.